

OCEANOGRAPHY FOR GEOGRAPHERS

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PREFACE

The science of Oceanography deals with the three dimensional oceans. Recently, since the International Geophysical year, it has become a study of international nature and responsibility. The modern methods of oceanographical researches are highly technical and mathematical beyond the approach of students of Geography.

This book has been written with the aim of presenting the study of oceans in a non-technical language for students of Geography in particular and of Oceanography in general. We have limited ourselves mainly to 'Physical Oceanography'.

The present study is the outcome of collection of datas widely scattered through innumerable journals and books. We have freely drawn references from them. Particularly, maps and charts have been adopted from other works. We are obliged to the various authors and publishers for the help we have taken in getting the factual information.

We also extend our thanks to Sri M. Aktar who has assisted in the preparation of maps and diagrams.

*Geography Department,
University of Allahabad
August 15, 1962*

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- 1993 Examine the salinity of open and partially enclosed ~~area~~ seas. Bring out the relationship between salinity and temperature.
- 1993 Attempt a classification of ocean deposits. Describe in detail the characteristic of Pelagic deposits
- 1992 What is coral reefs and how do they originate? Discuss the theory of Darwin in support of coral reefs formation.
- 1992 How are ocean currents caused? Describe the main currents of the Atlantic Oceans and their effects on coast lines.
- 1988 Describe the relief features of bottom of the Atlantic or Indian Ocean.
- 1988 Describe the Indian Ocean currents giving reasons for their ~~re~~ climatic influences on the adjoining regions.

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Oceanography, the science of sea, is a subject of modern growth though its foundations can be traced back to the earliest times. It is concerned with the elucidation of many intricate and complex problems of physical and biological nature and practical problems of sea which forms so large a part of the environment of mankind. According to H. A. Marmer,¹ "The name of oceanography, the science of the sea, embraces primarily the study of the form and nature of the oceanic basins, the characteristics of the waters in these basins and the movements to which these waters are subject to...And like other sciences now-a-days, it is growing on the technical contributions of specialists each engaged in cultivating intensively some small patch of the vast domain." Otis W. Freeman² stated that "Oceanography like Meteorology is a science which has grown from geographic soil. It is concerned with the hydrosphere, a very mobile part of the earth" and studies tides, currents, physical properties of ocean water, configuration of the coasts and the ocean floor, and life in the ocean as well as its regional distribution. It is intimately associated with the exact sciences. A very conclusive statement by J. Proudman³ states that Oceanography studies the fundamental principles of dynamics and thermodynamics in relation to the physical properties of the sea water and biological studies.

PLACE IN GEOGRAPHY

Geography, the science of the earth, is a synthetic science which largely depends for its data on the results of specialized sciences such as astronomy, physics, geology, oceanography, meteorology, biology and anthropology. It is both a descriptive and analytical science and apart from facts of location, direction and distance, almost every fact that it employs belongs quite as much to some other sciences. Thus its data is mostly assembled from diverse fields. Dr. G. K. Gilbert has rightly remarked that the geographer is, or should be, the great insect that carries pollen from field to field. A very comprehensive view can be taken from Fig. 1 which advocates the very principle of scientific trespass resulting in the cross fertilization of knowledge—the *summum bonum* of the subject of Geography. Since geography cuts sections through all the systematic sciences, there is an intimate and mutual relation between it and each of those sciences. The science of Geography, since its inception in antiquity up to the present time, includes definite aspects of all those terrestrial phe-

¹ Marmer, H.A., *The Sea*, p. 289.

² Freeman, Otis W., 'Geography Among Sciences', *Journal of Geography*, Vol. 50, May 1951, p. 207.

³ Proudman, J., Preface to the *Dynamical Oceanography*.

nomena (Land-Lithosphere, Air-Atmosphere, water—hydrosphere) which are now treated exhaustively under the heads of geology, meteorology and oceanography.

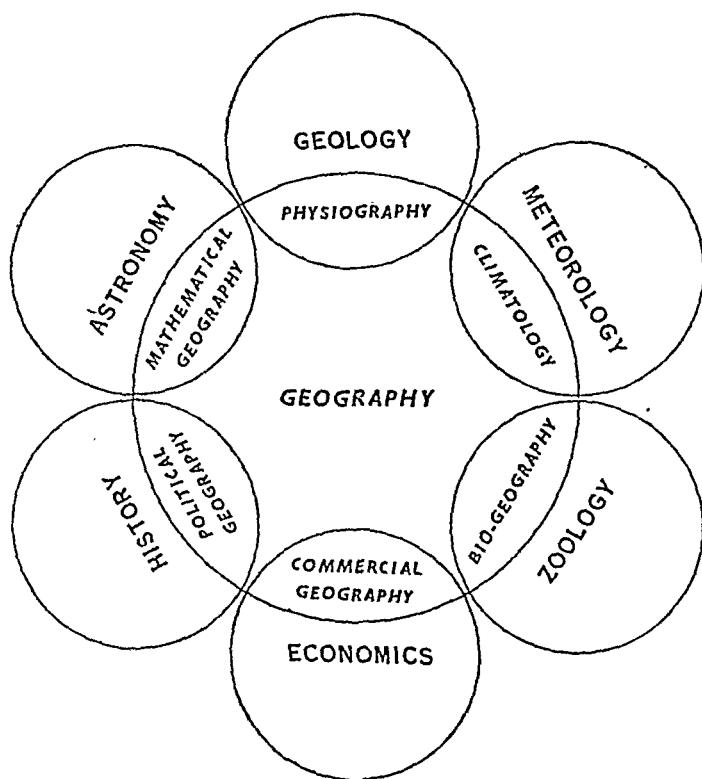


Fig. 1. Relation of Geography with other Sciences.

The science of oceanography, explaining the conditions of the hydrosphere, is the part and parcel of physical geography. For its data it depends upon geology, meteorology, physics, chemistry and biology of sea water. The significance and importance of oceanography in the science of geography can very well be realised when we think of the great expanse of the hydrosphere, covering about three-fourth of the earth's surface, that is the total water area of about 361,059,000 square km (71%), whereas the total land area is about 148,892,000 square km.

GROWTH AND HISTORICAL DEVELOPMENT

The foundation of oceanography can be traced back to the observations of naturalists and the records of seamen from the voyages of Phoenicians, Carthaginians and Greeks in the nearer parts of the Indian and the Atlantic Ocean outside the pillars of Hercules. The early period of its development (1000 B. C. to 2nd century A. D.) is divided into three stages :

(i) Traditional voyages crystallised in the knowledge of the world from Homer (1000 B. C.) to Hecateus (500 B.C.) showing the great river like 'oceans' surrounding the known lands bordering the Mediterranean. (ii) Discoveries of the astronomer Pytheas (4th century B.C.), a contemporary of Alexander. He imparted knowledge of latitudes and tides of different places. Further, the Greek scholar Strabo (1st century B.C.) wrote a comprehensive treatise on the physiography of land and sea. Later on, Posidonius asserted that he measured the sea in the neighbourhood of Sardinia to a depth of 1000 fathoms. (iii) This stage resulted in the contribution of a map by C. Ptolemy in 2nd century A.D. in which he represented the Indian Ocean as an enclosed sea—an error which remained uncorrected till the time of Captain James Cook in the 18th century.

With Ptolemy we come to the end of the period of the scientific Oceanographic researches of classical times. There was a faint knowledge and little progress in oceanography during the following period, known as Dark Age. This period was again followed by the Great Age of discoveries and explorations in 15th and 16th centuries which resulted in immense knowledge about oceans. During this period Prince Henry of Portugal surnamed 'The Navigator' founded his school of maritime research at Sagres near Cape St. Vincent on S. W. corner of Portugal in 1420. Later on, Columbus discovered America, Vasco da Gama opened the route to India and Magellan circumnavigated the globe. The achievements of this illustrious trio of the Great Age opened a new era of history of geography and oceanography. Hence in 1570, the world map of Ortelius showed enormous changes in the knowledge of land and sea.

Again, a period of comparative inactivity followed the Great Age and remained up to late in 18th century, when Captain James Cook (1728-1779) explored South Pacific Region. The knowledge and development of the science of the sea during 19th century is divided into three phases: (a) The period of Edward Forbes, (b) The period of Wyville Thompson and the 'Challenger' expedition, (c) The post 'Challenger' period of Sir John Murray and the modern oceanography. These three phases were marked by the pioneer work in marine biology, in the exploration of the depths of oceans, and the study of plankton, coral reefs and submarine deposits.

During this time the study of oceanography was directed towards more scientific lines. The data collection became important and so many scientific expeditions in the various oceans were carried out by the eminent personalities of the time. The following are the great contributors in oceanographic science during the 19th century.

1. *Edward Forbes* (1815-1854). Being a great naturalist and marine biologist, his contributions were mainly towards the distribution and varieties of sea animals in the water near Great Britain, Hebrides and Mediterranean up to a maximum depth of 230 fathoms from which he brought live star fish to the surface. In some parts of Atlantic he also studied bottom relief. His earliest works were the dredging in Irish Sea (1832-39), near Norway (1833) and in Shetland seas (1839-1845).

Further, in 1841 he was appointed naturalist to the 'Beacon' expedition, engaged on hydrographical work in Eastern Mediterranean. During

this work along the coast of Lycia, sites of about eighteen ancient submerged cities were discovered, and the result was published in '*Travels in Lycia*' in 1847. In his report as published in 1843, he mentioned on the distribution of animals in Aegean Sea. He defined eight zones of depth characterized by peculiar animals and the zero of animal life probably appearing about 300 fathoms, followed by the 'Azoic Zone'—a fact rather found to be erroneous. His another important contribution is in the form of a paper in 1846, 'On the connection between the distribution of the existing fauna and flora of the British Isles and the geological changes which have affected their areas.' In 1850 he prepared a remarkable map of the distribution of marine life over the oceans of the world.

2. *Wyville Thompson* (1830-1882). He was one of the most famous pioneers in the exploration of the depths of the ocean. During his early expeditions in "Lightening" (1868) and "Porcupine" (1869 and 1870), he explored the depths of the sea from Faroes in the north to Gibraltar and beyond in the south. Thus he was able to contradict Forbes' views that sea animals could live up to 300 fathoms only. According to him life was found up to 4000-5000 fathoms depth.

Thompson was most famous for his round the world expedition "Challenger", during 1872-1876. Thus for about $3\frac{1}{2}$ years the ship traversed 69,000 miles in the Atlantic and Pacific Oceans, and penetrated as far south as the Antarctica ice barrier. Soundings and dredging of 362 stations were taken which included enormous collections of marine organism, samples of bottom deposits (Diatom, Pteropod etc.) and water from all depths and all latitudes. His investigations were mostly centred in the Atlantic. Hence in 1877 he published a book named "Voyage of the 'Challenger'—The Atlantic" in which he gave detailed descriptions regarding Sargasso Sea, the bottom relief, temperature conditions in Faroe channel, and the mode of accumulation of deep sea deposits.

One of the important results of the 'Challenger' expedition was an increase in the knowledge of the details of structure and mode of formation of coral reefs and the preparation of world map showing distribution of pelagic sediments.

3. *John Murray* (1841-1914). He was known as the pioneer of modern oceanography and his investigations were done mostly in 'Triton' (1882) and 'Challenger'. He was the sole incharge of the Challenger office after Thompson. He discovered the exact nature of the submarine ridge, north-west of Scotland and named it as Wyville Thompson ridge. Further, during 'Challenger' expedition (1872-76) his work was to preserve and examine the nature of 12,000 samples of ocean deposits collected during the voyage. Later on, he published the results with the help of Renard.

Murray devoted special attention to three subjects of primary importance in the science of sea, viz., the plankton or floating life of the oceans, the deposits forming on the sea bottoms, and the origin and mode of formation of coral reefs. His classification of deep sea deposits into (i) Shore deposits, (ii) Globigerina ooze, (iii) Radiolarian ooze, (iv) Diatomaceous ooze, and (v) Red and Grey clays, is still adopted. During his 'Challenger' expedition round the world, he discovered various submarine volcanic elevations which helped him to present his most original theory of forma-

tion of "Atolls". Later in 1896-98 he took special interest to study the nature of reef in Funafuti Atoll.

His most famous works are: Narrative of the Expedition, Deep Sea deposits (1891), summary of the Results (1895) and The Oceans (1913). His last great scientific expedition "Michael Sars" was conducted in North Atlantic in 1910, when he was 70 years old. The investigations included the fish zones, the 'mud line' (placed at 100 fathom depth) and general deposits in the bottom.

In the end we can say that Murray's oceanographic work was not limited to any particular region or special series of problems but varies in subject-matter and world wide in extent. He was a great traveller and explored the sea from Spitzbergen in the north to Antarctic in the south. He contributed many important maps, e.g. the map of Pacific showing 32 deeps, which are deeper than 3,000 fathoms.

4. *Louis and Alexander Agassiz* (1807-1873-1910). Both father and son are known for their individual contributions towards the knowledge of the sea. Louis Agassiz migrated from Switzerland to U.S.A. in 1846 where he became famous by his lectures on natural sciences. From 1847 onwards he was in direct touch with U.S. Coast Survey vessels. By the time in 1851, he discovered important characteristics of Florida Reefs and Keys (succession of concentric reefs separated by deep waters). He was probably the first to notice that so-called coral reefs are not always formed of coral, but are chiefly made up of coral-lives and limestone algae. In 1865 he organized expedition to Brazil, and in 1870 along West Indies region in the coastal survey steamer 'Bibb' for deep sea dredging. In 1871-72, an extensive dredging on "Hassler" ship was done round the South American coast from Florida to San Francisco.

Alexander Agassiz's first expedition was with his father in 'Bibb' vessel. Later on, successive voyages in 'Blake' and 'Albatross' of coast survey were conducted in South Seas and Pacific. His voyages covered more than 100,000 miles in the tropical seas and he personally made more deep sea soundings than all the oceanographers taken together. In 'Blake' expedition (1877) in Caribbean Sea he was deputed as a mining engineer to improve the apparatus for deep sea works. Hence he substituted steel wire rope for dredging in place of hemp. He devised new form of double edge dredge-tow net which could capture the plankton from any depth of the sea. During further voyages of 'Blake' along the Atlantic he observed about the origin and location of Gulf Stream extending from Florida to Newfoundland. With this he could emphasize the relation between the currents and the bottom fauna.

He was a great oceanographer and Murray in the following words commends his work : "Agassiz's researches in the Atlantic resulted in very definite knowledge concerning the submarine topography of the west Indian region, and of the animals inhabiting these seas at all depths." His examination of the coral growth on Florida coast in "Blake" was supported by "Challenger" results—that is, thinner shells disappeared with increasing depth whereas in shallower depth majority of shells reached the bottom before being dissolved. Hence the disappearance of carbonate of lime from deep sea deposits was noted. This explanation made it possible to argue that atolls and barrier reefs are formed due to biological, mechanical, and chemical processes in the ocean and not due to subsidence.

Alexander's last 30 years of life were totally given for the solution of coral reef problem. He made the following coral reef expeditions, e. g., Bahamas & Cuba 1892; Bermuda and Florida 1894; Barrier Reef, Australia 1896; Fizi Islands 1897-98; and Maldives 1902. And during his trip to Maldiva (Indian Ocean) in 1901-2 he came to the conclusion that subsidence hypothesis of Darwin was not applicable in coral reef areas.

His last expedition was carried out in Eastern Pacific in 'Albatross' (1904-5) in which he discovered a region of abundant radio activity and least bottom deposit.

5. *Prince of Monaco* (1848-1922). His voyages, in 200 tons schooner 'Hirondelle' and 1420 tons ocean going vessel 'Princess Alice', systematically recorded details of Gulf Stream, Azores, Spitzbergen, Mediterranean, and Atlantic (from Equator to Arctic circle). The details of the voyage were published in "Re'sultats des Champagnes Scientifiques."

His major contribution is towards the knowledge of various new deep sea Atlantic animals. In 1902 he found the difference in the temperatures of Atlantic and Mediterranean on both the sides of Gibraltar. The waters in Atlantic at 800 fathoms depth are found to be slightly warmer than the waters of similar depth in other parts of ocean, because there is a surface current of lesser temperature and salinity from Atlantic towards Mediterranean, whereas an outflow of relatively warm and saline waters of Mediterranean mixes in Atlantic waters near about 800 fathoms depth. Again in 1902 he discovered an enclosed basin (Monaco deep) in which temperature at 1645 fathoms was 5°C , though the temperature of the surrounding Atlantic Ocean at this depth is not more than 3°C . Hence it was first estimated and later confirmed that a submarine barrier between 850 and 900 fathoms depth separates the warmer water of the basin from the open waters of the Atlantic.

To the credit of Prince of Monaco, other important contributions were the discovery of the exact nature of the direction and velocity of currents in the North Atlantic, specially near Azores; the preparation of world map—"Carte Generale Bathymetrique des Oceans"—showing the depths; and the building of a magnificent oceanographical museum in Monaco and the Oceanographic Institute at Paris.

Recent Major Oceanic Expeditions. In recent times since the rapid increase in the study of the exact sciences, various major oceanic expeditions carried out an intensive study of the oceans. Among the recent expeditions are the Gazelle expedition in South Atlantic, Indian and Pacific Oceans; Michael Sars in North Atlantic (1910), the Fishing Commission and Albatross expedition in East Pacific; and the U.S. Coast and Geodetic surveys which produced valuable charts. Later on, the 'Meteor' expedition in 1925-27 covering 67,000 miles determined the circulation of the South Atlantic and employed the method of sonic sounding to get the depth of the oceans; the Carnegie expedition in 1928, covering 45,000 miles made the magnetic surveys and sonic sounding observations of temperature, salinity, reefs, bottom deposits; the Dana expedition for Pacific and Indian Oceans; and the Snellius expedition under E. W. Scripps, covering the East Indian Archipelago and Atlantic, collected facts regarding continental shelves. Other expeditions were the Discovery II expedition (1950-51)

in Southern Seas; the Challenger expedition (1951); the Danish expedition (1951-52) and various Geodetic and coastal surveys of British Admiralty and U.S.A.

Further, Nansen, Amundsen, Pettersson were famous oceanographers who worked in North Atlantic and were associated with the above expeditions. Shepard, an eminent oceanographer of the modern times, worked in Scripps Institute of U. S. A. He made a detailed survey of the bottom topography of Atlantic and Pacific Oceans and prepared maps of canyons found on the shelves and slopes of the continents. More recently, the geophysical researches during the International Geophysical Year in the polar waters have resulted in more advanced information. The major expeditions are Nautilus and Commonwealth Trans-Antarctic expedition.

The recent decade is marked with the world-wide scattering of institutes and research laboratories for the study of the science of oceans. Among the important ones are the Naval Hydrographic Office, the Coast and Geodetic Survey, the Scripps Institution of Oceanography in U. S. A.; the Geophysical Institute, the Hydrographic Biological Commission in Scandinavia; the Marine Biological Association of U. K.; the Oceanographic Institute in Paris; the Research Institute of Marine Fisheries; Institute of Oceanography in Canada and S.C.O.R. (Special Committee on Oceanographic Research) which plans and co-ordinates the work of many countries. And above all, the oceanographic researches are carried out on international basis, e.g. the projected survey of the Indian Ocean undertaken from 1960 onwards by American, British, Indian, Soviet and other oceanographers.

SCOPE AND IMPORTANCE

The voyages and research expeditions for scientific marine investigations clearly picture out the frontiers and subject-matter of oceanography. The aims and objects with which these expeditions had been launched in the past as well as in the recent times, form the ingredients of this science whose main object is the study of the oceanic environment and its infinite complexities. Further, by a critical survey based almost entirely on the work of living as well as classical personalities specific references can be made to limit the scope of oceanography.

Embracing all studies pertaining to the seas, oceanography is a 'cosmopolitan activity'. That is, it is concerned with the explanation and elucidation of many complexities of physical and biological nature. It deals with the scientific as well as practical problems. Above all, it is the result of the study of different sciences which enable us to cover the sea in all the possible ramifications. So its general progress and development depends upon the technical contributions of special sciences engaged separately or in collaboration. Hence, as a science it adopts deductive and inductive methods of approach to the vast domain of oceanic environment.

Broadly speaking, the science of sea is divided into two broad spheres: Physical Oceanography and Marine Biology. Physical Oceanography considers sea as a 'fluid in motion' subjected to internal and external forces. The prime emphasis in this field has been directed towards an understanding of the structure and circulation of the ocean water. So the contents of

Physical Oceanography are: the origin, extent and nature of ocean-basins; the physiography of sea bottom and coastal areas; physical properties of sea waters—salinity, temperature, pressure, density, compressibility, viscosity—and water masses and their general distributional patterns; thermodynamics of ocean water—wind currents, wind waves, tide and tidal currents, other currents of the oceans. Further, the theories and principles about different physical properties and thermodynamics of water are included in the study of Physical Oceanography and so in it the application of hydrodynamics is of fundamental importance.

Recently, Physical Oceanography also takes into account the atmosphere above oceans and thus it is significant in meteorological studies. This branch of study is known as Marine Meteorology. The development of this subject is due to Maury of U. S. Navy who was first to lay the subject into coherent whole. It deals with that portion of the atmosphere which overspreads the great masses of water. It is very difficult to draw hard and fast rules to separate Physical Oceanography from Marine Meteorology, as both are intimately related to each other.

The necessity of such a study arises due to the fact that seamen over oceans require not only knowledge about general conditions prevailing over the ocean, but also of the phenomenon which happens in the atmosphere due to the interactions between the atmosphere and the ocean. So an acquaintance with marine meteorology helps the navigator to sail safely. Without the barometer and thermometer even a well known oceanographer cannot be successful over the seas. Hence Marine Meteorology includes within its domain the study of the atmospheric pressure, the temperature of the air and of the sea, the winds, the law of the storms and hurricanes and their regions and tracks, ocean currents, icebergs, and weather charts, etc.

The study of the animals of the oceans is under the province of Marine Biology—a vast subject in itself, though only a branch of Zoology—which investigates the causes and origins of animal and plant life. Marine Biology is a very important branch of Oceanography so far as the economic utility is concerned, for an enormous amount of sea food is annually consumed by the people of the earth. The vast domain of oceanic life and its subtle responses to the conditions and changes in the temperature and movement of the ocean water varying with depth, latitude, belts and the land masses, is the subject-matter of Marine Biology. In details, the subject-matter is composed of : the chemical composition of sea water; marine organisms—plant groups of sea, plankton, and floating animals, and their distribution; and lastly, the sea as a biological environment.

Further, to know the comprehensive nature of oceanography from another standpoint, it is divided into hydrography, metabolism, bionomics and tidology. Though it is possible to make a valuable contribution to any single aspect of oceanography without any reference to the other branches, yet for better understanding of the different aspects of oceans as a geographical environment, there is a need of synthetic approach to biology and hydrography of water bodies. Hence a sharp boundary cannot be drawn in the treatment of the vast subject-matter about oceans. The same idea is expressed in the prospectus which in 1908 accompanied the first number of *'Internationale Revue der gesamter Hydrobiologie and Hydrographie'* : "Above all, the editors recognise the necessity of a synthesis of

our biological and hydrographic-geological knowledge of the waters. These two spheres of investigations are inseparable since the water, whether as river, lake or sea, is never a factor in the shaping of the earth without being also a medium for life and on the other hand is never a medium for life at the same time having an important influence in the shaping of the earth surface."

The study of oceanic environment is essential for the modern student. There are various aspects by which this study can be viewed to know the potential as well as direct value of the oceanic environment. The marine research expeditions and trips under the able masters like Edward Forbes, Wyville Thompson, Sir John Murray, Dr. John Hjort, Alexander Agassiz and more particularly, the recent advances in the knowledge of the sea due to technological and scientific advancement have all the more enhanced the importance of this branch of knowledge.

✓ Besides the above basic studies, a geographical approach of oceanography should also include :

- ✓ (i) the inter-relationship between sea and atmosphere and the effect on weather;
- (ii) the problems and prospects of oceanic navigation; ✓
- (iii) the possibilities of developing planktonic food resources; ✓
- (iv) the development and conservation of world fisheries and exploration of other new food resources; and ✓
- (v) the geophysical research with the aim of knowing the effects of various forces under the sea. ✓

OCEANOGRAPHY AND OTHER SCIENCES

Oceanography is a science which has taken its birth from geographic soil. Geography is a very broad subject and its most unique and important contribution is that of tying together the various sciences and other subjects. These various sciences tend to overflow from one compartment into another and fuse together to make a single whole. Similarly, oceanography is also intimately associated with the exact sciences because of its field being too vast and too subtle. The bull's eye view of the classification of physical sciences puts oceanography among earth sciences which are closely inter-related and integrated for the elucidation of the subject-matter (Fig. 2).

† *Geology* is concerned with the elucidation of the history of the earth and its province begins when earth crust gets solid. Due to its comprehensive nature and having five distinct branches—cosmogony, physical geology, petrology, palaeontology and stratigraphical geology—it covers and elucidates the basic concepts of Physical Oceanography which is concerned with the origin and permanency of ocean basins, and with the nature of oceanic bottom. Further, a close relationship exists between physical geography or physiography which has three divisions, all depending on the laws of geophysics, viz., geomorphology, oceanography and climatology. Practically, for its vital issues of the origin, age and composition of oceanic basins, the science of oceans depends and has to maintain a close inter-relationship with geology and physical geography.

When oceanography is concerned with the sea as a fluid, its thermodynamics is to be studied. Hence it depends upon *physics*, *mathematics* and

hydrodynamics. For a better and comprehensive knowledge about the different motions of sea water, viz., wind waves, currents, tides and tidal waves etc., it seeks help from applied mathematics by using different principles and concepts of hydrostatics and hydrokinetics. This approach and elucidation of facts about sea as a fluid gives it a place in exact sciences and explains the dependence of oceanography on them.

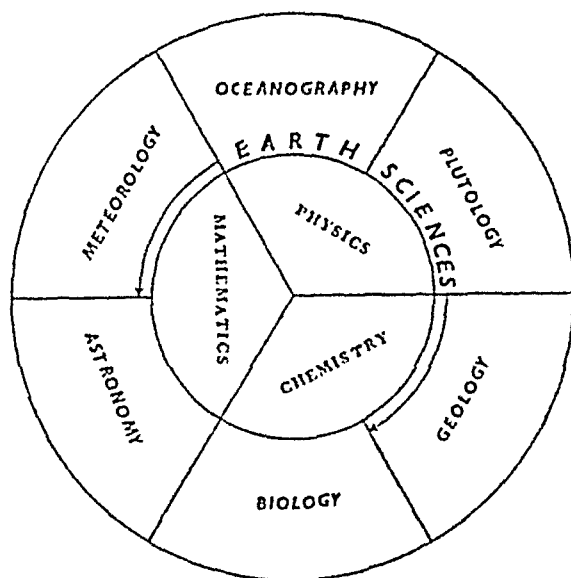


Fig. 2. Bull's eye Classification of Physical Sciences.

Oceanography and *meteorology* have a common place of origin, that is, they have their foundations on geographic soil. Moreover, due to the nature of the scope and the methods of treatment, oceanography is regarded as 'Inverted Meteorology' (meteorological studies in the ocean, directed upside down). The science of meteorology treats various phenomena of atmosphere including weather and climate. Owing to the complexities of the phenomena of the atmosphere and their frequent changes, meteorology is the most difficult of all the sciences. It is regarded as the result of the composite arrangement of the portions of many allied sciences, such as physics, chemistry etc. Oceanography and meteorology are related when marine meteorology which treats the atmosphere over the great masses of water is taken into account. Its central theme that the sun's rays penetrate more deeply into the ocean and diffuse uniformly, makes the inter-relationship between atmosphere and hydrosphere quite different from that of land areas and atmosphere. This, in turn, is the part and parcel of Oceanography in which a significant place is given to the treatment of various properties, i.e. insolation; temperature distribution and heat budget of the oceans; pressure and wind system and their interaction on the biology, physics and chemistry of the water masses. Further, *climatology*, the science of climate, is also one of the allied sciences needed

in oceanographical study in which a due consideration is given to various climates, their distribution on the land and the effect of water masses on their characteristics or *vice versa*. The study of the climatic regions of oceans is also an important branch of study.

Chemistry, Zoology, Botany have also some contributions towards the subject. Chemistry is concerned with the composition of bodies and with the changes they undergo. It has the analytical as well as the synthetic approach to the facts of inorganic and organic fields. It is one of the constituent sciences of oceanography which deals with the chemical composition of water bodies and the animal and plant life and their distribution in relation to the regional chemical composition of water. Zoology and botany form a special branch of oceanography, viz., marine biology, a vast subject in itself, which deals with habitants of the oceans and their ecological problems, i.e., problems arising out of the relation of organisms to one another, and to their environment. Thus a biologist has a wide scope to study the structure and physiology of the organisms and the zoologist has the great variety of sea water organisms.

The rapid progress of the exact sciences in recent times has led to a rapid transition from a geographic to a geophysical treatment of the problems of Oceanography. The application of physical-mathematical principles has made it a branch of Geophysics. Recently, a widespread net work of geophysical investigations regarding the oceanic floor has been set up in various localities. The investigations were carried out regarding the determination of gravity, the seismic prospecting, the heat-flow measurements, the structure of a number of coral atolls and volcanic islands, the structure of deep sea trenches and the oceanic structure. The noteworthy names regarding the above specialized investigations are: Hecker, O. (1903-1910) made first geophysical investigations of the ocean floor, Vening Meinesz (1923-1938) made Gravity Expeditions at sea, Duffield, W. G. (1924) worked on the problem of measuring gravity at sea, Cooper and Bullard (1949-1950) worked out the British submarine gravity and in the eastern North Atlantic Ocean, Worzel and Shurbet (1955) published a number of gravity sections across the continental margin of the eastern United States, and the Institute of Geophysics of Los Angeles made gravity measurements in Eastern Pacific, the Atlantic and the Indian Oceans. The seismic prospecting has been carried out by many among whom Weibull (1947-48), Swallow (1954), C. B. Officer (1955), and Gaskell (1954) are important. Regarding the heat-flow measurements, Bullard studied the Atlantic Ocean, Revelle and Maxwell (1952) studied the floor of the eastern North Pacific Ocean. Lastly, Gaskell and Swallow worked on two Pacific atolls, Dobrin and Perkins studied the Bikini atoll.

Conclusively speaking, the science of oceanography is a composite science in its nature and in the methods of approach to the problems and the facts of the vast domain of water. The province of oceanography overlaps the various territories of different earth sciences and it seeks help from them in order to elucidate the facts of sea around us.

Chapter 2 | LAND AND WATER HEMISPHERE

The omnipresence of changes in nature have made the problem concerning the origin of the ocean basins and land and water arrangements rather difficult. Hence in spite of various approaches and combined knowledge from all the sources, we have a vague understanding of it. The broad features of the earth, i.e. land and sea, are termed as 'Relief Features' of the first order by R. D. Salisbury. These are the important geological features formed by various internal forces. Due to great antiquity of the earth (2 billion years), its origin and the particular arrangement of ocean bodies and continents render doubts as regards the authenticity of any single idea which attempts to prove the origin of such distribution of land and sea. But constant attempts from past to present have succeeded in putting forth certain ideas as regards their origin and in presenting certain peculiarities of form and structure in the distribution of land and sea. Many of these approaches regarding the origin of land and sea partially depend for their explanation on the fundamental concepts of the origin of the earth itself.

DISTRIBUTIONAL PATTERN OF EARTH

Before taking the problem itself, we must have an account of major structural units of the face of the earth. The following patterns call for an explanation :

1. (a) The continents of the Laurasia group.
(b) The intervening North Atlantic and Arctic oceans.
2. (a) The continents of the Gondwanaland group.
(b) The intervening South Atlantic and Indian oceans.
3. The oceanic basin of the Pacific covering the above groups like a huge girdle.

Further, there are certain features in the distribution of land and sea on the surface of the earth that also call for explanation :

1. The marked concentration of land in the northern hemisphere and of water in the southern hemisphere, combined with a reversal of this contrast in the polar regions—north polar oceanic basin to south polar continental region.
2. The northern roughly annular continental land region which sets over against the southern annular oceanic region.
3. Tri-radiate arrangement of land and sea round the poles.
4. Almost all the continents are of triangular form with their base along the Arctic. North and South Americas form isosceles triangle with base on Arctic and apex at Cape Horn. Similarly Eurasia forms two triangles with base at Arctic and apex at Cape Horn and Tasmania.

Separately, all the continents form triangular shape with the base in the north and the apex towards the south.

5. Various oceans also have roughly triangular shapes with base in the south and apex in the north. The Atlantic has base between Cape of Good Hope and Cape Horn, and the apex in the east of Greenland, the Indian Ocean has its apex in Bay of Bengal and Arabian Sea, and the apex of Pacific lies near Aleutian islands.

6. The occurrence of 81% of the land in the land hemisphere which has its pole in Brittany and the predominance of water in the Water Hemisphere which has its pole near New Zealand.

7. Great land margins running obliquely towards and across the equator and consequent southern extension of the three continental blocks of South America, Africa and Australia.

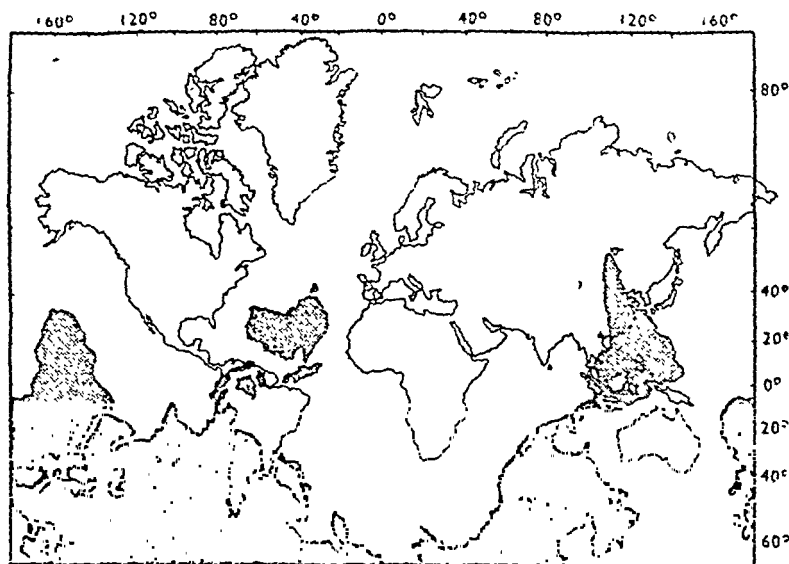


Fig. 3. The Antipodal position of Land and Water. (After Gregory 1899).

(By permission, from 'Introduction to Geophysics', by Benjamin F. Howell, Jr., Copyright 1959, McGraw-Hill Book Company, Inc., N.Y.)

8. The antipodal arrangement between land and sea: 44.6 % of the surface having sea opposite sea, only 1.4% having land opposite land and 95% of the land being antipodal to sea as shown in Fig. 3. The only exception to land and sea antipodal arrangement is Patagonia and New Zealand situated opposite China and Portugal.

THEORIES OF ORIGIN

In the middle of 18th century two main theories were proposed, based on two contrasting concepts : (i) one proposes a single body in the begin-

ning which broke up into different units, and (ii) the other postulates that earth and other planets are the result of the piecemeal accretion of scattered particles through space. These concepts explain the origin of the earth through the process of condensation.

Nebular hypothesis. The most popular at present time is the Condensation or Nebular Hypothesis, based on the Newtonian law of gravitation. It was expounded by the German philosopher Immanuel Kant in 1755, who speculated the earth and our solar system as condensed from a rotating diffuse cloud of primordial matter of dust and gas. The germs of the Nebular Hypothesis were contained in the Cartesian philosophy in the work of Descartes (1596-1650); in the mathematical concepts of Leibnitz (1646-1716) and of Swedenberg (1688-1772); and slightly in the ideas from atomistic school of Greek philosophers like Democritus and Lucretius. Besides Kant, a French mathematical physicist astronomer, Savant Laplace (1796), and an astronomer observer, Sir William Herschel, also arrived at similar, if not identical, conceptions of the universe.

Laplace, avoiding Kant's error regarding the primordial matter of Nebula, assumed the sun as the rotating disk of hot gaseous matter of radius greater than the distance from sun to the outermost planet. The constant cooling, contraction, increase in the speed of rotation, and consequent increased centrifugal force caused the separation of rings from the equatorial circumference which ultimately aggregated to form the planets. The same process has resulted in the origin of moon as a satellite to our earth. In due course of time moon and earth cooled down, resulting into the rocky crust. According to the assumption, the superficial layer is however cooled rapidly but the internal mass of earth cools and contracts slowly, leaving the upper crust unsupported, which later sinks and fits on the lower layer, hence, resulting into crumples, folds and deformations. The higher areas thus became continents and lower areas gave birth to oceanic depressions in which the water vapour previously held in the atmosphere formed the primitive oceans.

But during the course of time this Nebular Hypothesis of Kant and Laplace became untenable, mainly because of the fact that the total angular momentum of all planets is not sufficient for the break-up of Nebula by excess of rotation caused by constant cooling and contraction.

Planetesimal hypothesis. The concept of the formation of planets by the piecemeal accretions of smaller particles scattered through the space was proposed by T. C. Chamberlain (1904) in the form of Planetesimal hypothesis, though it has been postulated earlier by G. H. Darwin and N. Lockyer who advocated for an original cloud of meteoroids of various sizes. Chamberlain in his elaborate studies with the astronomer Moulton proposed that matter was originally in the form of dust grains which he called 'planetesimals'. In his opinion planets are held to be bi-parental in origin as a result of the nature of the sun and the inter-action of sun (erruptive) and another star (projectile of suitable mass in the form of tidal disruption) leading to the ejection of small jets of solar matter. These jets in their turn became nuclei for different planets which due to aggregations of planetesimals grew into the planets of our system.

The oceans began to form in depressions when the amount of water vapour in the atmosphere reached saturation point and was collected into

the hollows and pits created due to volcanic action. Further, evolution of these relief features is accounted for by the weathering process and the gradual increase of the size of earth by the accretion of planetesimals. The arrangement of oceans and continents is explained by a series of meridional and oblique yield tracts which divide up earth into quadrilateral areas. The yield tract in the growing earth is the result of a mechanism which allows earth body to change its shape with the change in the rotation. The change is due to the stresses which are greatest near the centre and least at points near the poles. These stresses are relieved by the actual dislocation and fracture and the consequent rearrangement of the material of the earth crust. According to these yield tracts, the oceanic areas are arranged in pairs: North and South Atlantics, North and South Pacifics, and the Indian Ocean corresponding to the depression occupied by the Mediterranean, the Baltic, the Black, the Caspian, the Red Seas and the Persian Gulf. There is a symmetry with regard to the situation of each pair of oceans, that is, northerly areas lie obliquely to the west with respect to southerly oceanic depressions. Further, the areas delimited by yield tracts and having elevations are the loci of continental plateaus.

Tidal hypothesis. Among fragmentation theories, the most important is that of J. H. Jeans and Jeffreys, who believed in the bi-parental origin of earth due to the tidal effects on the sun by the passing star of a greater magnitude which caused various nuclei in the form of planets and thereby producing fold and depressions, i.e. land areas and ocean basin.

ARRANGEMENT OF OCEAN BASINS

All the above theories account for the origin of earth but do not give a very clear picture of the arrangement of oceanic basins and continental areas of the earth.

The continental land and oceanic areas are distinctive areas defined as the large theatres in which geological dramas are enacted. It is here that the relief features of second order (plains, plateaus and mountains) and the relief features of the third order (features of arid, glacial and river topography, etc.) are in constant transformation and change. Various processes, since the past history of geological actions, are responsible for ordering the distribution and shapes of relief features of first order. The arrangement of these oceanic basins and continental nuclei bear a definite geometric arrangement which calls for its own explanation. Various attempts have been made in connection with the relationship of oceanic basins and continental land by taking into consideration the process of accretions, gravity and rotation.

TETRAHEDRAL HYPOTHESIS

A tetrahedron is a solid body which has four equal plane surfaces, each of which is an equilateral triangle and has four solid angles, in each of which three edges or di-hedral angles meet. The edges of the tetrahedron, where different faces meet, represent those parts of the surface which are farthest from the centre. Experiments as regards contraction of sphere of flexible metal proved the deformation of sphere into a tetrahedron. So the reduction of volume of the earth through cooling and contraction results in tetrahedron earth.

Lowthian Green (1875) initiated the Tetrahedral hypothesis to attempt an explanation of the following facts : the marked concentration of land in the northern hemisphere and water in the southern hemisphere combined with a reversal of this contrast in the polar regions; the antipodal relations between land and sea and the southerly extension and tapering off of the three continental blocks of South America, Africa and Australia. The concept of Tetrahedron is in close conformity with the concept of cooling and contracting globe and an irregular collapse of the crust of the earth on a shrinking interior. The basis of this change has been the resultant volume of the earth due to shrinking whereas the surface area remains the same. The Tetrahedron as the possible form of change or deformation from sphere of the earth, indicates an evolutionary development in the distribution plan of the earth.

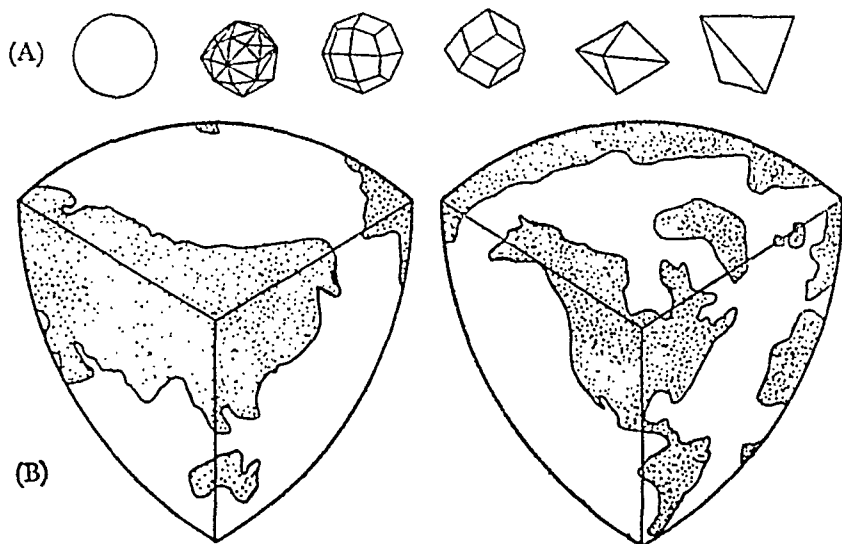


Fig. 4. (A) A series of polyhedrons from the sphere with greatest volume to the tetrahedrons with least volume.

(B) The tetrahedral earth (After Griffith Taylor).

The series of Polyhedrons shown in Fig. 4¹ put the tetrahedron with its four flat surfaces, having the minimum volume on the lowest ladder, as against the spheroid shape (having the smallest superficial area for a given volume of the earth) on the highest ladder.

Lowthian Green claimed to have seen a rough tetrahedral arrangement of land and sea areas. The three solid angles of tetrahedron lie in the land areas corresponding with three ancient land areas of the globe which are : the Laurentian or Canadian Shield in the Hudson Bay area; the Baltic Shield in the Baltic Sea area covering the tracts of the countries of Finland, Sweden and N. W. Russia; and Angara Shield in East Central Siberia. The pivot on which the tetrahedron is assumed to stand covers the area of the Antarctic continent which is of the same geologic antiquity

¹ Hobbs, *The Earth and its Facial Feature*, p. 87.

as the above three shields. Further, the antipodal arrangement of land and sea areas is explained by the four flat faces of the tetrahedron which are occupied by the oceanic basins towards the southern apex. The continental areas on the edges of tetrahedron also converge towards southern apex, proving the tapering of the continents and oceanic basins in the south, as shown in Fig. 4. Further, land areas around the Arctic Ocean also fit in the form.

Taking into consideration Sir Charles Lyell's concept of 'uniformitarianism' and Professor James D. Dana's concept of 'permanence of the ocean basins', the geological thoughts of the day were greatly changed to believe in the slow and moderate geological changes in the earth's physiognomy. Having the concept of slow evolution as our basis, the outline of evolution of earth's physiognomy reveals the present tetrahedral arrangement in process as a result of constant evolution in the spheroid earth due to cooling and shrinking. The earth's physiognomy at the close of Eozoic era was very simple, having only six knots as the nuclei of the present continental masses. These are : the Laurentian, the Baltic and the Angara shields in northern hemisphere and in southern hemisphere the Brazilian, the African and the Australian shields. These were subsequently enlarged by marginal growth resulting into the quite otherwise arrangement of oceans and continents. At the close of Paleozoic era as shown in Fig. 5¹ the leanings were from east to west in the shape of the

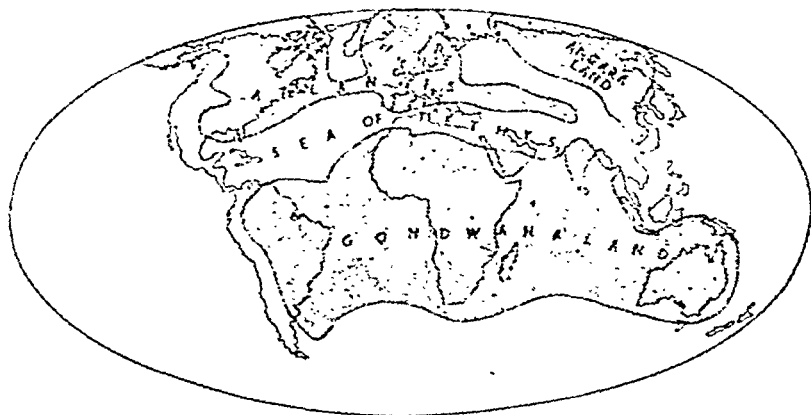


Fig. 5. The continents at the end of Paleozoic Era. (After Arldt).

'Atlantis' in north and the 'Gondwanaland' in the south with the intervening sea of 'Tethys'—as opposed to the present northerly and southerly pattern of continents and oceans. But the present form and pattern of continents and oceans came into being in the Mesozoic era by foundering off all parts of the 'Gondwanaland' and the 'Atlantis'.

Though the tetrahedron theory is consonant with the views of cooling and shrinking globe, but it is criticised on the ground that the final figure of tetrahedron does not correspond with the figure of equilibrium. On

¹ Hobbs, *The Earth and Its Facial Features*, p. 87.

the basis of present arrangement of land and sea, the maximum land exposure lies at 66° north latitude where 80.1% of the land is above sea level as compared with 43.6% at 30° . But contrary to it this maximum would be required at 30° north according to the tetragonal concept. Further, the south pointing fingers, in the form of continents, should fall at the interval of 120° but in reality from east to west the interval is 115, 155 and 90 degrees because the continent taperings pass nearly at 20° E, 135° E and 70° W.

CONCEPT OF ISOSTASY

Besides the tetrahedron hypothesis, there are many concepts about the arrangement of oceans and land areas. The concept of Isostasy takes into account the mechanical stability or balance between the upstanding areas and the low basins on a rotating earth. The state of compensation is brought about by the materials of which they were formed. The principle of Isostasy does not clarify the particular arrangement of oceanic and land areas, but it accounts for the depressions, elevations and their nature. The main principle behind isostasy is that the density and the gravity of matter varies according to rock formation in the upper part, below which is a level of compensation where densities are uniform throughout any given depth in the shell of the earth. The density is taken in inverse proportion to the height of the area. So the mountain areas formed of rocks of less density are of high elevation in comparison to plateaus which consist of heavy matter. And the oceanic depressions in comparison to the continental elevations (sial) consist of heavier matter of high density (sima). But each and every type of area is exerting an equal amount of downward pressure at the level of compensation. This interpretation is of great value to the geographer and to the geologist in understanding the structure and relief features of the earth. It accounts for the depressions and elevations in the form of oceans and continents.

OTHER CONCEPTS

Lapworth assumed the continents and oceans as the result of folding of the earth crust on a very large scale. He supported that anticlines of composite nature formed the continents and synclines formed oceans. So according to him, the continent of America is broad composite arch, with a vast median sag in the place of central plains of the continent. Similarly, the Atlantic Ocean is a vast downfold with a central upfold representing the Challenger-Dolphin ridge in the Atlantic Ocean. This concept of upwarping and downwarping of Lapworth had been modified and substantially made more appealing by the scientist Love in 1907. Through mathematical insight and by taking into consideration that centre of gravity is not the geometric centre of the body, he visualised a series of harmonic deformations in upwarps and downwarps on the earth as symbolic of continental and oceanic areas respectively. Thus he accounted for the major relief features of the first order.

The next hypothesis previous to the Continental Drift Theory of A. G. Wegener was quite in vogue and based on the study of rotational stability by Jeans and Sollas. Taking the birth of the moon and formation of the Pacific depression as accidental, this concept believes in the 'Pear-shaped' form of the earth as shown in Fig. 6.¹ In this earth form, the stalk of the

¹ Morgan and Woolridge, *The Physical Basis of Geography*, p. 34.

pear is assumed to represent the small island continent, antipodal to the land hemisphere and the location of oceans is represented by the areas around the girdle of the pear. Afterwards by putting more evidences in favour of this concept, Sollas made it more appealing. He visualised that Africa as the centre of land hemisphere is antipodal to the water hemisphere and the Pacific basin. The Atlantic is taken as the break in the continuity of land hemisphere which is duly supported by the various structural similarities between the two coasts of the Atlantic Ocean.

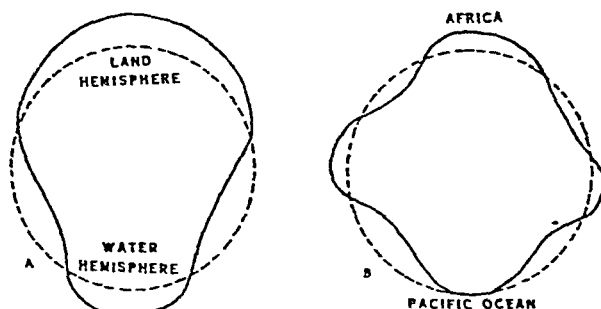


Fig. 6. Jean Sollas' hypothesis of earth deformation. (After Sollas)

Very recently Umbgrove (1947) and Vening Meinesz (1945) believed in the concentration of subcrust at convection currents just below the continents; and the oceanic basins are taken as the places from where these subcrustal currents transfer the magma and pile it up in the form of continental blocks and thus accentuate the difference between the relief features of the earth crust. This concept to some extent is explanatory of the tetragonal arrangement of sea and land areas. It further accounts for the various characteristics in the distribution of sea and water area, viz., the tapering of continents in the south and predominance of land areas in the north.

One more theory, the Tidal Resonance Theory about the origin of the earth relief features, is no longer considered to be important because of many objections. This concept believes that in the initial stage of molten state, a part of original crust was removed in the form of the moon thus leaving a depression named as the Pacific basin. Consequently, the other parts of the crust broke apart and floated towards the Pacific to cover the depression area. This floating resulted into the formation of other oceans and the separation of land areas and continents.

CONCEPT OF DRIFT

So far the idea of permanency of ocean basins has been the main point on which various theories have been put forward. Due to evidences in the field of geology, palaeo-climatology, geophysics and palaeontology, the concept of permanency of ocean basins has given way to the idea of horizontal movement of earth crust and displacement of blocks of continents on the subcrustal floor of sima. The concept of drift, though it recently got prominence, is the result of various scientific approaches during the last three centuries. As early as 1620, Francis Bacon had given a slight push to the concept of drifting of earth crust which resulted into the

arrangement of oceanic and land areas. Afterwards, Buffon (1780), Young (1810), R. Owen (1857), A. Snider (1859), E. Wettstein (1880), O. Fisher (1882), C. B. Warring (1887), W. H. Pickering (1907) were the main architects of this concept.

The real advocates of continental drift theory were F. B. Taylor in 1908, H. B. Baker in 1911 and A. Wegener in 1912, who convincingly put forward vast domain of evidences in their support of the concept which led to the entrenchment of deep conservation in the approaches of geology for explaining the relief features of the earth crust. In modern times this concept is thought to be scientifically tenable by geologists, physicists and biologists. It has also been responsible for the clear interpretation of various puzzling problems such as the arrangement of oceanic and land areas, tectonic forces, ice age, animal and plant migration etc. Modern thought is hospitable to the theories of drifting and rifting of continents.

Taylor's theory. The concept developed by F. B. Taylor in 1910 bears the idea of continental drift towards Equator from North and South Poles and the other towards west. Originally the concept of Taylor was developed only to explain the formation of great mountain ranges of Tertiary era. He took the Tertiary era to be more vigorous in relief formations and imagined that the source of energy was external. That is, the creation of moon and tidal force in late Cretaceous time increased the rotation of the earth. The creation of Alpine-Caucasus-Himalayan mountain belts supported the idea of a drift of the continents equatorward. The equatorward drift has caused the stretching of the earth crust in north and south. The result is the creation of Baffin Bay, Labrador Sea, Davis-Strait in the north, and the creation of Great Australian Bight and Ross Sea around the continent of Antarctica in the south. The Arctic Basin separating Greenland and Siberia is also the result of the equatorward stretching. Taylor further suggested that South America was separated from Africa in the Permian time. This led to the creation of the Atlantic Ocean. The evidence to this fact is brought by the remarkable similarity of west coast of Africa and Europe to the east coast of the Americas.

There are severe objections to this theory. The first and the foremost is the assumption that external force of the drift was due to the moon's tidal force and the continuous increase in the rotation of the earth. This fact seems quite vague and contradictory as this moon's force, if sufficient to drift the continents, can also put brake on the rotation due to friction. Secondly, this concept is also silent in explaining the early orogenic cycles prior to the Cretaceous period when the moon took birth. But in the opinion of Arthur Holmes: "Taylor must be given credit for making an independent and slightly earlier start in this precarious field. His immediate object was to account for the distribution of mountain ranges."¹ Thus the theory was propounded to explain the formation of folded ranges of the earth crust but it also gives a fair idea about the formation of the oceanic basins.

The Wegenerian hypothesis. The late Professor Alfred Wegener, a Professor of Meteorology and Geophysics in the University of Graz, in 1912, after rejecting the idea of permanency of oceanic basins and the creation of earth's relief features by sinking of the earth crust, put forward the

¹ Holmes, Arthur, *Principles of Physical Geology*, p. 490.

concept of 'Displacement Hypothesis'. The three successive editions in 1915, 1920 and 1922 of his book, *Die Entstehung der Kontinente und Ozeane*; and the English version of the last edition of 1922, viz., *The Origin of Continents and Oceans* by J. G. A. Skerl in 1924, put forward the thesis of Continental Drift. These editions afterwards led to active controversy.

The theory of drift had been proposed by Wegener in order to explain the land and sea distribution as well as the larger climatic aberrations of the past. For this he gathered evidences from the works of geologists, palaeoclimatologists, palaeontologists and geophysicists. The present arrangement of continents and oceanic basins is regarded as a result of the fragmentation by rifting and drifting apart of the original continental mass known as 'Pangaea' surrounded by a universal ocean 'Panthalassa'. Wegener, like Suess, supposed that the continental mass which is called 'Pangaea' existing in the Carboniferous time (due to lack of evidence he does not take pre-carboniferous conditions) is a continuous layer of 'Sial' over the layer of Sima forming the surface of the primaeval Pacific Ocean (Panthalassa). The assumption of Wegener is based upon "the well-known hypsographic curve of Krummell and the rather less known frequency curve of Trabert. The former curve shows the relation of the deeps, deep sea plain, continental slope and shelf as a continuous graph; the latter shows the percentage of the earth's surface, plotted as frequencies of the whole area of the globe for any height above or depth below sea level."¹ According to Wegener and his continental drift theory, the Carboniferous period is the beginning for the present arrangement of land and sea areas.

The concept of continental drift as observed by Arthur Holmes and Du Toit² should be responsible for explaining the process operating within the earth and forming important features. It should be capable of:—

(a) Disrupting the ancestral Laurasia and Gondwanaland (combined in Pangaea) into gigantic fragments and carrying them outwards, i.e., Africa and India towards the Tethys; Australia, Antarctica and South America out into the Pacific; and North America away from Eurasia.

(b) A transfer of a part of the Pacific water to fill up the tension basins making the other oceans.

(c) The recognition of drift as a progress that has operated throughout geological time. Wegener postulated two main directions of movements: towards the west and towards the Equator. "The forces invoked by Wegener to produce the drift were differential gravitational forces acting upon the protruding blocks of sial."³ The relation of the centre of gravity and the centre of buoyancy of the moving mass is the cause for the equatorward drift of continental block of sial. And for the westward drift of the crust, the tidal forces of sun and moon are responsible, as moon then was rotating faster.

¹ Steers, J. A., *The Unstable Earth*, p. 161.

² Holmes, Arthur, *Principles of Physical Geology*, p. 565, and Du Toit, Alex. L., *Our Wandering Continents*, p. 36.

³ Woolridge, S. W. and Morgan, R. S., *An Outline of Geomorphology*, Second Edition, 1959, p. 39.

Evidences in support of the Drift. In support of the westward and equatorward drift and the consequent asundering of the parts of the existing 'Pangaea', Wegener had marshalled a wide range of evidences from various fields. He has seen the parallelism and the same geologic history of the two opposing coasts of the Atlantic—the western coasts of the continents of Europe and Africa and the eastern coast of Americas—still matching 'as closely as the lines of a torn drawing would correspond if the pieces were placed in juxta-position' and he took it as an evidence and advocated the idea of 'jig-saw fit' of the two coasts where the structural trends and direction of geological grains were of the same order and magnitude. Hence by putting all the drifted parts of land in one map showing the state of Upper Carboniferous time, he made a single and compact continental mass 'Pangaea'. He also worked out a definite geological chronology for the assumed continental movements.

Drift and the arrangement of Oceans and Continents. The present distribution and arrangement of oceanic basins and continental masses is the result of this drift, as shown in Fig. 7¹ in which the map is drawn at the edge of the continental shelf. It may be noted that North America must be greatly distorted and India drawn out to join Africa. Wegener also stretched North and South Americas, so that they were joined from the beginning.

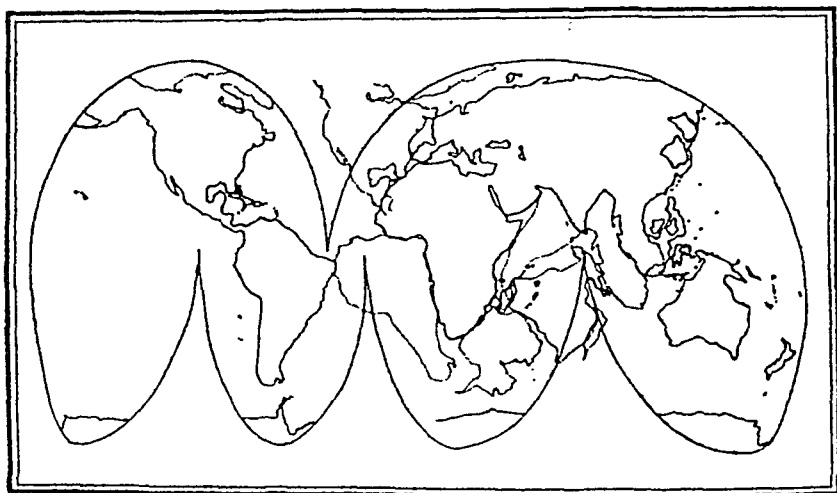


Fig. 7. Grouping of continents previous to drifting as conceived by A. Wegener. (By permission, from 'Introduction to Geophysics,' by Benjamin F. Howell, Jr., Copyright 1959, McGraw-Hill Book Company, Inc., N.Y.)

As postulated by Alfred Wegener, the Upper Carboniferous time was marked by the overwhelming expanse of primaeval Pacific Ocean and the continental mass of 'Pangaea'. The major part of 'Pangaea' was practically covered by the shallow seas, specially over areas which in time to come became the folded mountain ranges. The shallow seas over the old

¹ Benjamin F. Howell, *Introduction to Geophysics*, 1959, p. 283.

mass were mostly in the central belt and on the western margin, and the rest of the area was free from encroachment of water. Further, in late Paleozoic time the whole mass broke and the separation proceeded. The Jurassic era witnessed the asundering of the southern and western parts of this great land mass. At the same time, the rifting and drifting apart of the Americas towards west caused the birth of Atlantic and further, the part of Gondwanaland moved northward thus creating the Indian Ocean. By Pliocene time, the distribution of land and ocean came into being, similar to the present conditions, with the only exception that the pole was not at its present position. According to Wegener the North Pole in the Silurian period was in latitude 14°N and long. 124°W ; in Carboniferous period in lat. 16°N and long. 147°W and in Tertiary period in lat. 51°N and long. 150°W . The creation of oceans and separation of continents created a tension which, in the opinion of Wegener, was the cause for the creation of great rift valleys of Africa and Asia and Rhine in Europe.

The evolution of the Pacific and other oceans under the Displacement hypothesis had been dealt more elaborately by Alex. L. Du Toit, who like Wegener, also conceived the Pacific as twice its dimensions in the beginning and playing the passive role in the evolution of earth features of the first order. The evolution of Pacific had been marked by three-sided movements of the earth crust of varying degree and magnitude. The result of these movements was the shrinking in size. The westward drift of the two Americas marked with the regular advance of North America, due to lesser opposition from the foreland of the Pacific. Hence the eastern boundary of the Pacific is comparatively straight and less complicated. The movement of Asian and Australian blocks into the ocean of crustal waves resulted into the lagging behind of the continental masses. Thus the western part of the Pacific region became island strewn. In the south, the continental mass of the Antarctica failed and lagged behind the advance of South America and Australia. The result of this fact is the general stability of the Southern Pacific Ocean. So the general asymmetry of the two Pacific coasts is accounted for by the differing degrees of mobility, amply supported by the volcanism and the 'metallisation agencies'.

The Atlantic Ocean, equivalent to half of the Pacific Ocean, makes S-shaped outline, for, as the coast of African Sahara bulges westward, so does the north coast of South America recede into the Caribbean embayment. Similarly while Cape Sao Roque projects, the Gulf of Guinea recedes in the same direction. The general outline of the Atlantic basin had been formed mainly due to the westward drift of Americas where the North American block advanced slightly more than the South American block. As regards mid-Atlantic Ridge, viz. Dolphin Challenger Rise, supporting the volcanic islands of Iceland, Azores, Ascension, Tristan da Cunha and Bouvet, various theories and ideas had been advanced. According to Wegener the ridge had been regarded as the former land surface left behind when the Americas moved off the coast of Europe and Africa in a westward direction. Further, the creation of the Arctic Ocean and the North Polar Sea was regarded due to the equatorward drift of the masses. The actual place of rifting between Arctic and Atlantic was marked by the existence of 'Poseidon' depression as called by Schuchert. Unlike the Antarctic basin, the Arctic basin at no time remained a stable region, but during every epoch it was crossed by some synclinal depressions and marked by ejections of basalt during the Cretaceous-Tertiary period.

The Indian Ocean, slightly lesser in extent than the Atlantic Ocean, consists of a medial rise from Gauss Berg in the Antarctica through St. Paul, New Amsterdam, Chagos, Maldiva and Laccadive islands. The same concept about the origin of Atlantic and Atlantic medial ridge can be put forward for the explanation of the ridge and basin formation of Indian Ocean. All these features owed their origin to the sub-parallel slices of Gondwanaland that had rifted and drifted apart but without complete severance, as the result of India moving away from Africa. The southern region of the Indian Ocean in the proximity of the Antarctica is the result of westward as well as equatorward drift of the land. This area is comparatively stable.

Objections to Wegener's Ideas. The Wegenerian concept assumed certain prerequisites which were criticised by various scientific experts. Among those who put forward their adverse opinions were E. W. Berry, A. Born, Bowie, Gregory, Hobbs, Jeffreys, Kober, von Ihering, van der Gracht, Holmes and Staub. The constant question put forward against the concept is about *Pangaea* which remained intact due to some force and did not break up until Mesozoic time. Those gravitational forces which are responsible for the movement of rifted blocks must be in operation throughout, and measurements made in 1823, 1870, 1907 and 1922 on possible movement of Greenland on westward side have failed to detect any evidence of drift.

It has been rightly remarked that no force is adequate to produce continental drift on such large scale, because the tidal force invoked by Wegener would need to be 10,000 million times more powerful than it is at present, and this force working opposite to the rotation of the earth would have stopped earth's movements. Similarly, the equatorward force is also insufficient on the basis of the measurement of relative high viscosity of the substratum. Wegener's 'jigsaw fit' of two opposing coasts of the Atlantic seemed to be the main attraction and a point of advocacy, but recent investigations have brought forth the realities otherwise. The presence of granitic layer in the Atlantic ridge makes the similarities of the coastlines of European and African continents insignificant. Further, the similarity of the Paleozoic fauna and flora as assumed by Wegener has doubtful characteristics. Schuchert and Gregory by their investigations made these biological resemblances insignificant. The parallelism in the stratigraphical and structural features of the two sides of Atlantic is also not as perfect as proposed by Wegener. Further, the rifting of the Atlantic coast may present the problem of the continental shelves which would unite before the actual coasts meet. Again, India would be seen in juxtaposition with Madagascar and Africa. If Himalayas are unfolded then India moves a greater distance towards south.

EXTENT OF THE OCEANS

The oceans form one of the major units of environment of mankind. Out of three-cellular arrangement of land, sea, and atmosphere, the sea on the surface of the earth covers a major area. The distribution of land and water on the surface of the globe is most irregular. Water areas are more extensive in comparison to the land areas. The knowledge of the exact extent of the various seas and land areas is the result of the recent

scientific advancements. The extent of sea in classical, medieval and modern times varies according to the increasing knowledge about the earth crust itself and according to the attempts to measure the extent of land and sea areas of the globe. Broadly speaking, serious attempts towards knowing the extent were firstly made by English investigators. Previous to this, all knowledge about sea was fragmentary, partly based on mercantile activities of the different nations and partly on the religious orthodox beliefs. Dr. Long, in 1742, estimated the land-water ratio as 1 : 2·81, or 26% to 74% and in 1837 Professor Rigaud placed this ratio as 26·6 to 73·4 per cent.

The idea of classical times about the extent of the sea was coloured with certain prejudices based on religion and on the idea of supernatural elements of nature. Different people had different conceptions about the extent of the oceans and land areas and the map that showed this arrangement was a faint picture full of irregularities. The earliest knowledge about the sea and its extent came from the different people surrounding the Mediterranean. In the Greek-records and in the Babylonian and the Hebrew scriptures the total land of very small extent is shown to be engirdled by a vast ocean. Hence the centre of all activities was formed by the Mediterranean Sea. A somewhat clear picture about the sea was later on summarized in the writings of the Greek historian Herodotus (450 B. C.) who told about the indefinite extent of land on the northern side and about the existence of the Atlantic. At the same time he rejected the idea of encompassing ocean. Later on, the validity of these facts was confirmed by the writings of Pytheas, who established the intimate relation between the moon and the tide. In the writings of Eratosthenes, we get an idea of a great extent of sea and the possibility of circumnavigating the globe. He also regarded Africa as being surrounded by the ocean. Even up to the time of Strabo, the centre of all marine activities was the Mediterranean.

After Greek references, the Roman records are of great importance as regards the general pattern of sea and land areas. About half a century after the appearance of Strabo's *Geography*, Pliny's *Historia Naturalis* accounted for the whole knowledge in a condensed form. But after a period of about three quarters of a century, Ptolemy noted the Indian Ocean as an enclosed sea due to the presence of a continental mass, viz. Terra Incognita, and held the view that westward across the Atlantic, the subcontinent of India was situated at a distance much less than the reality. This idea resulted in the accidental discovery of New World.

The activities of the Vikings and the mercantile activities of the European nations resulted in more compact knowledge about the extent of the seas, particularly in north and west. The approximately correct knowledge about the extent of sea came as a result of great marine activities of Columbus, Vasco da Gama and Magellan in the Great Age of Discoveries and Exploration in the 15th and 16th centuries. Magellan revealed the true extent of the sea on the earth. As a result of these marine activities between 1492 and 1522, a world map of land and sea was prepared.

Further, with the advance of knowledge and techniques new discovered areas of sea and land were added on the world map showing their extent. The discovery of North-West Passage and North Pole

added to the knowledge about the Arctic Ocean and the adjacent seas. The attainment of South Pole in the 19th and in the first quarter of 20th century revealed the true extent and nature of the Arctic Ocean. Similarly the development of instruments for determining position at sea with precision and the development of marine crafts added much to the exact knowledge which delineated correctly the position and extent of land and sea on the world map. So the extent and the general pattern of arrangement of oceanic basins and continental masses is very recently visualized and mapped accurately.

U 2 5

WATER BODIES AND THEIR NOMENCLATURE

It would not be out of place to deal with the system of nomenclature used for different water bodies. A further treatment in the following chapters of the book will be confusing without a brief explanatory note about the classification of the oceans and seas and their nomenclature. Several systems for naming parts of the oceans are employed and the whole system becomes confusing and sometimes misleading, but because of long usage it is so firmly fixed that a change would lead to further practical difficulties. Primarily, the classification of water bodies is based mainly on the following factors, viz., position, size, form, water-salinity, tides, currents, and mode of origin.

K 2

5 2 6 5 8

The classification, *according to the position and situation*, becomes quite unscientific because of several confusions as regards the nature of different bodies. The water bodies having extensive areas are known as oceans, while those penetrating deeply into the land and having an access to the ocean by a narrow outlet are differently named as inter-continental seas or partially enclosed seas, e.g., the Mediterranean Sea, the Arctic Ocean and the Gulf of Mexico. The classification according to the size brings main difference between various water bodies, viz., the Indian Ocean having an area of 73 million sq. kilometres, the Berring Sea with an area of $2\frac{1}{2}$ million sq. kilometres and the North Sea of $\frac{1}{2}$ million sq. kilometres though the nomenclature is same. The factor of form and configuration brings three main types into the system, viz., ocean, seas narrowly connected and seas widely connected with the larger bodies, and the completely enclosed seas.

The constituent property of salinity of sea water also makes a basis of classification of different water bodies. The variation of this property into several types depends upon the extent of the sea, and on the connecting passage between sea and the ocean. The classification based on salinity is given in Table 1.

The classification based on the movements of water bodies has two main types : Oceans with independent tidal waves and currents, and Seas with dependent systems. The factor of origin of water bodies gives two main types : Areas of deep oceanic basins like the Indian, the Atlantic Oceans etc. and the Seas found at the edges of the continents by sinking of continental crust and dislocation of the crust, like Hudson Bay and Red Sea respectively.

As the contents of oceanography deal with the form of water bodies, and also with the distribution of properties and living organisms and the nature of the currents, the system of classification of oceans and their nomenclature should be satisfactory to explain the inherent qualifica-

TABLE I¹
Examples of seas, classified according to salinity
 (The salinity of 35 mille is normal)

I	II	III
Salinity above normal	Normal	Below normal
Red Sea (37-41)	Caribbean-Mexico (35-36)	(a) <i>Slightly under</i>
Persian Gulf (37-38)		Arctic Ocean (20-35)
Mediterranean (37-39)	Bass Straits (35½)	N. Australian Sea (33-34)
	Gulf of California (35-35½)	Bering Sea (28-33)
		Sea of Okhotsk (30-32)
		Sea of Japan (30-34)
		Andaman Sea (30-32)
		North Sea (31-35)
		English Channel (Irish Section) (32-35)
		Gulf of St. Lawrence (30-32)
		China Sea (25-35)
		(b) <i>Much below</i>
		Baltic Sea (3-15)
		Hudson Bay.

tions set up by the above definition. For the general classification of water bodies, the works of Schott (1926, 1935), Wüst (1936) and of the International Hydrographic Bureau (1937) may be referred to.

Distribution of land and sea. The detailed knowledge about the pattern of land and sea distribution brought into the forefront the overwhelming importance and extent of oceans on the earth surface. "The hydrosphere covers nearly three-fourths of the earth's surface as a single and continuous expanse of water surrounding four great insular land masses known as continents.... Thus there is a total land area of 148,892,000 sq. km. and a total water area of 361,059,000 sq. km., i.e. 29% of land and 71% of water, or a ratio of 1 : 2.43."²

¹ Jenkins, J. T., *A Text Book of Oceanography*, p. 10.

² *Encyclopaedia Britannica*, Vol. 16, 14th Edition, N. Y. 1929, p. 680.

The details about the various oceans and water bodies have been given in Table 2, so that an exact knowledge about the expanse of sea water may be comprehended.

TABLE 2¹
Mean Area and Volume of Oceans and Seas

Name	Area sq. km.	Volume cu. km.
Atlantic Ocean	82,441,500	323,613,000
Indian Ocean	73,442,700	291,030,000
Pacific Ocean	165,246,200	707,555,000
Oceans	321,130,400	1322,198,000
Arctic Sea	14,090,100	16,980,000
Malay Sea	8,143,100	9,873,000
Central American Sea	4,319,500	9,573,000
Mediterranean Sea	2,965,900	4,238,000
Inter-continental Seas	29,518,600	40,664,000
Baltic Sea	422,300	23,000
Hudson Bay	1,232,300	158,000
Red Sea	437,900	215,000
Persian Gulf	238,800	6,000
Smaller enclosed Seas	2,331,300	402,000
Bering Sea	2,268,200	3,259,000
Okhotsk Sea	1,527,600	1,279,000
Japan Sea	1,007,700	1,361,000
E. China Sea	1,249,200	235,000
Andaman Sea	797,600	694,000
Californian Sea	162,200	132,000
North Sea	575,300	54,000
English Channel and Irish Seas	178,500	10,000
Laurentian Sea	237,800	30,000
Bass Sea	74,800	5,000
Fringing Seas	8,078,900	7,059,000
Seas enclosed and fringing	39,928,800	48,125,000
Hydrosphere	361,059,200	137,032,500

¹ Encyclopaedia Britannica, Vol. 16, 14th Edition, N.Y. 1929, p. 680.

The above table originally prepared by Kossinna (1921) gives striking contrasts in area and volumes of various water bodies. Of the total expanse of water bodies, the oceans, viz., the Atlantic, the Indian and the Pacific, constitute 90% of which the Pacific Ocean itself covers the largest expanse of water. Similar interpretations can be given as regards the appropriation of total volume of the hydrosphere. Among internal continental seas, the Arctic Sea, stretching in the north of three great continents of North America, Asia and Europe, covers about one-half of the total area of the internal continental seas. Hudson Bay and Bering Sea are ranked first among the smaller enclosed seas and the fringing seas respectively.

Table 3 gives the conclusions derived from Table 2 as regards area and volume of the different water bodies. Broadly speaking, the percentage of area and volume of internal-continental seas have a marked difference which can be ascribed to the topographical characteristics of water bodies.

TABLE 3

Name	Percentage of total area	Percentage of total volume
Oceans	88.91	96.49
Internal continental seas	8.17	2.96
Smaller enclosed seas	.63	0.029
Fringing Seas	2.21	.51

The distribution of land and water on the globe according to latitudes in the northern hemisphere and southern hemisphere is very irregular. The arrangement of water bodies brings forth the fact that in the northern hemisphere water covers only 60.7 per cent, whereas in southern hemisphere it is 80.9% of the total area. It follows that out of the total water hemisphere (70.8%), 43% is in northern hemisphere and 57% is in southern hemisphere. Speaking in terms of water and land, we can divide the earth surface into water and land hemisphere. 'According to recent measurements, the centre of the land hemisphere is on the coast of France, near Croisic, at the mouth of the Loire (lies at 47.25°N., and 2.5°W). The centre of the water hemisphere lies in the Pacific Ocean south-east of New Zealand (47.25°S., and 177.5°E).¹ The boundary of land hemisphere is formed by the circumference of the circle which is drawn with a radius equal to the distance from the mouth of Loire to Singapore. The circumference passes through Singapore, east of Japanese Islands, Peru and Southern Brazil and thus includes whole of Africa and Asia and excluding East Indies, North America, Europe and part of South America—north of a curved line joining Peru and Southern Brazil. The water hemisphere includes the area circumscribed with the circle having a radius equal to a distance from New Zealand to the north-west tip of Sumatra; thus it

¹ Jenkins, J. T., *A Text Book of Oceanography*, p. 6.

TABLE 4

Showing Distribution of Water and Land Between Parallels

Latitude	Northern Hemisphere			Southern Hemisphere				
	Water (10 ⁶ km ²)	Land (10 ⁶ km ²)	Water (%)	Land (%)	Water (10 ⁶ km ²)	Land (10 ⁶ km ²)	Water (%)	Land (%)
90—85	0.979	...	100.0	...	...	0.978	...	100.0
85—80	2.545	0.384	85.2	12.8	...	2.929	...	100.0
80—75	3.742	1.112	77.1	22.9	0.522	4.332	10.7	89.3
75—70	4.414	2.326	65.5	34.5	2.604	4.136	38.6	61.4
70—65	2.456	6.116	28.7	71.3	6.816	1.756	79.5	20.5
65—60	3.123	7.210	31.2	69.8	10.301	0.032	99.7	0.3
60—55	5.399	6.613	45.0	55.0	12.006	0.006	99.9	0.1
55—50	5.529	8.066	40.7	59.3	13.388	0.207	98.5	1.5
50—45	6.612	8.458	43.8	56.2	14.693	0.377	97.5	2.5
45—40	8.411	8.016	51.2	48.8	15.833	0.594	96.4	3.6
40—35	10.029	7.627	56.8	43.2	16.483	1.173	93.4	6.6
35—30	10.806	7.943	57.7	42.3	15.782	2.967	84.2	15.8
30—25	11.747	7.952	59.6	40.4	15.438	4.261	78.4	21.6
25—20	13.354	7.145	65.2	34.8	15.450	5.049	75.4	24.6
20—15	14.981	6.164	70.8	29.2	16.147	4.998	76.4	23.6
15—10	16.553	5.080	76.5	23.5	17.211	4.422	79.6	20.4
10—5	16.628	5.332	75.7	24.3	16.898	5.062	76.9	23.1
5—0	17.387	4.737	78.6	21.4	16.792	5.332	75.9	24.1
90—0°	154.695	100.281	60.7	39.3	206.364	48.611	80.9	19.1
All oceans and seas								
361.059 × 10 ⁶ km ² , 70.8%								
All Land								
148.892 × 10 ⁶ km ² , 29.2%								

covers the Atlantic, the Indian and the Pacific and the Antarctic Oceans and Australia, East Indies and southern part of South America.

The extent of land and water between parallels of latitudes gives some broad features of their relationships. For the support of further details table 4¹ showing the distribution of water and land according to Kossinna (1921) is given.

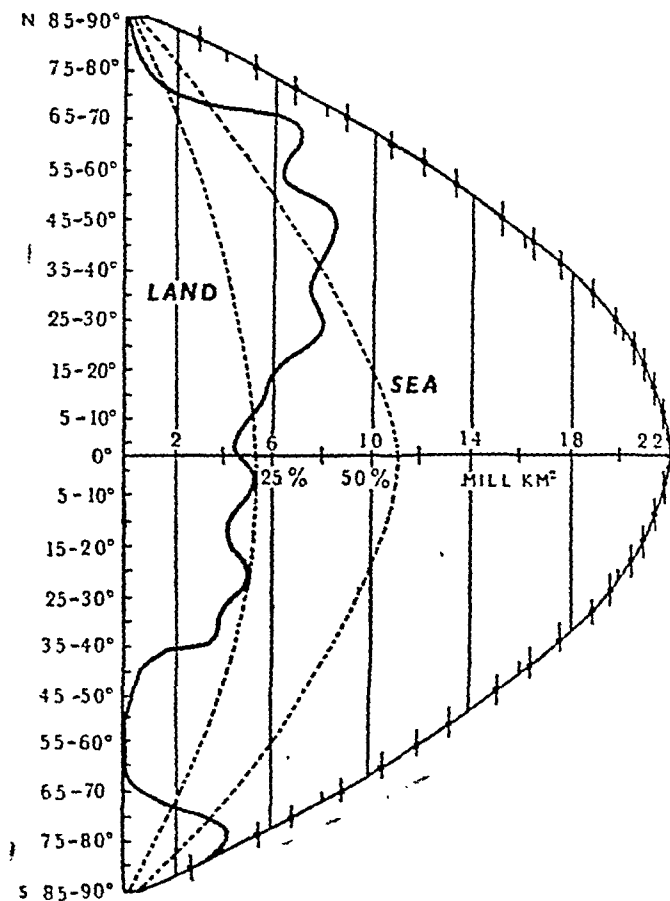


Fig. 8. Percentage distribution of water and land areas in five degree zones. (A. Defant).

According to the figures given by Dr. Erwin Kossinna, a German oceanographer, we can visualize the zonal distribution of land and sea, stretching through various latitudes on the globe. Fig. 8² very

¹ Sverdrup and others, *The Oceans*, p. 13.

² Defant Albert, *Physical Oceanography*, p. 4.

clearly shows the same results about the land and sea distribution in the southern and northern hemispheres. So, in between 80° and 90° latitudes, in the southern hemisphere the land dominates whereas in the northern hemisphere the water is prominent, due to the presence of the Antarctica continent and the Arctic Ocean respectively. Further, equatorward up to 70° north and south, the above pattern repeats itself. After 70° N and S-towards the Equator the land sea ratio changes and the arrangement is reversed due to predominance of the three great northern continents in the northern hemisphere and predominance and great expanse of the Pacific and the Indian oceans in the southern hemisphere. So between 35° and 65° latitudes the land amounts to 24% of the total area of earth surface in the southern hemisphere and 55.4 per cent in the northern hemisphere. Further, equatorwards due to the tapering of the northern continents, the land percentage diminishes in the northern hemisphere and so the sea occupies a major space; whereas in the southern hemisphere, due to the broadening of South America and Africa, and due to the presence of Australia, the land percentage increases. But still there is a predominance of water in these latitudes in southern hemisphere. Again, it is of interest to note that if we divide the globe into zones of 10° latitudes, then out of 18 zones the sea dominates in 13 zones. Further, it is visualised that the sea constitutes the dominant feature in each zone but not to the same extent. The land and sea ratio in the northern hemisphere is 1:1.5 and in southern hemisphere it is 1:4.

recording apparatus. The time interval between the emission of the sound wave and its reception as an echo is calculated with reference to the velocity of sound in water. The sounding of the ocean depths by means of sonic depth finders is an outstanding improvement. Not only is it more rapid but it can also be accomplished while the ship is moving. The result is that the depth of the sea is known in considerable details and a comprehensive knowledge about the diversity of features of bottom relief is gathered. A comparative study of profile of South Atlantic by wire sounding method and by sonic sounding method illustrates the importance of the latter.

HYPSOGRAPHIC OR HYPSONETRIC CURVE

The principle behind the Hypsographic curve is the representation of topography and relief in relative values. The relative representation is always taken with reference to the sea level and so the form and magnitude of elevations or depressions are thus represented. It brings out clearly relative importance of features that are found in the depths of the sea and on the land surface and shows the relative areas occupied by the different depths and heights on the surface of the globe.

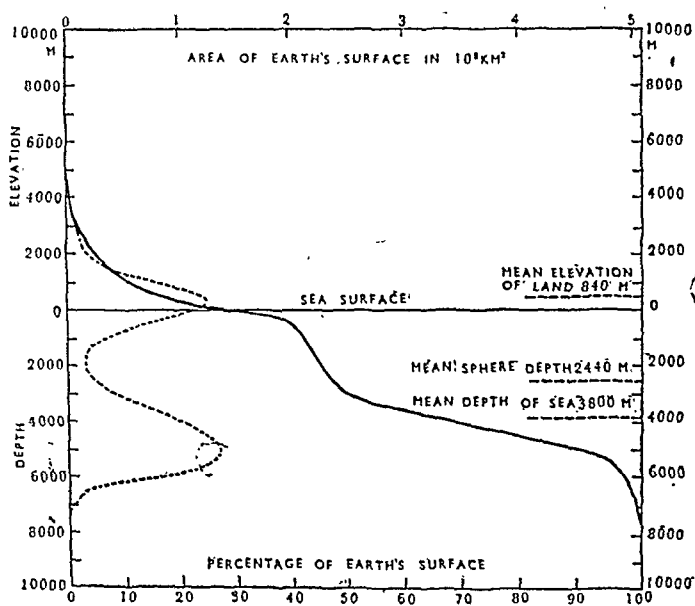


Fig. 9. Hypsometric Curve and Frequency Curve.

(By permission, from 'Physical Geography', by P. Lake. Copyright 1958. University Press, Cambridge.)

The Hypsometric curve, as shown in Fig. 9, is a typical double skew curve giving maxima at + 230 and - 4420 m. (Kossinna). It represents two undisturbed original levels in the crust. 'The curve, nevertheless, sets out in obvious fashion relationships that have been determined by the relative densities of the land and oceanic areas, the degree of

isostatic adjustment, etc.¹ The Hypsographic curve should not be considered as an average profile of land and sea surface because it does not consider the location of different depths and heights. The extent of areas is represented along the horizontal line and the vertical line represents the heights and depths. In Fig. 9,² the Frequency curve has also been drawn showing the proportions of land at various altitudes and of oceans at various depths. The Hypsographic curve of land surface elevation originally was computed by Kossinna in 1921, but it has very recently been modified by Sverdrup in 1942 due to the addition of recent data about the bottom relief of the oceans.

The curve and relief of earth surface. The heights of the continental masses and the depths of the oceanic bodies can be interpreted through the above hypsographic curve. An attempt was made by Sir John Murray to determine the extent and the proportion of land of various altitudes and the proportion of ocean floor at various depths as given in the following table.³

TABLE I

Height in feet (land)	Area (Million sq. miles)	Per- centage of whole globe	Depth in feet (Ocean)	Area (Million sq. miles)	Per- centage of whole globe
Over 12000	2	1	0-600	10	5
6000-12000	4	2	600-3000	7	3
3000-6000	10	5	3000-6000	5	2
600-3000	26	13	6000-12000	27	15
0-600	15	8	12000-18000	81	41
			over 18000	10	5
	57	29		140	71
<i>Mean Elevation of Land—840 m., Mean Depth of Sea—3800 m. Mean Sphere Depth—2440 m.</i>					

Particularly, the oceanic floor is divided into a few zones varying in character according to the depth. The mean depth of sea is 3800 m. Before going into further details about the various zones of relief of oceans, it would be more scientific to give the details about the percentage of area of depth-zones of various oceans and seas in a tabular form which would help in the elucidation of relief features of different water bodies by means of co-relation.

According to Table 2,⁴ the area of bottom relief of all oceans above the mean depth of the sea is insignificant as compared to the areas below the mean depths of the sea. This is because of the major feature of the extensive sea plain formed just below the continental slope of sea.

¹ Du Toit, Alex. L., *Our Wandering Continents*, 1957, p. 261.

² P. Lake, *Physical Geography*, 1958, p. 150 (Edition for India).

³ P. Lake, *Physical Geography*, 1958, p. 149 (Edition for India).

⁴ Sverdrup, Johnstone & Fleming, *The Oceans*, Table 5, p. 21.

TABLE 2
Percentage of Area in Various Depth Zones

Depth Interval	Including Adjacent Seas				Excluding Adjacent Seas			
	Atlantic	Pacific	Indian	All oceans	Atlantic	Pacific	Indian	All oceans
0—200 m ...	13.3	5.7	4.2	7.6	5.6	1.7	3.2	3.1
200—1000 ...	7.1	3.1	3.1	4.3	4.0	2.2	2.7	2.8
1000—2000 ...	5.3	3.9	3.4	4.2	3.6	3.4	3.1	3.4
2000—3000 ...	8.8	5.2	7.4	6.8	7.6	5.0	7.4	6.2
3000—4000 ...	18.5	18.5	24.0	19.6	19.4	19.1	24.4	20.4
4000—5000 ...	25.8	35.2	38.1	33.0	32.4	37.7	38.9	36.6
5000—6000 ...	20.6	26.6	19.4	23.3	26.6	28.8	19.9	26.2
6000—7000 ...	0.6	1.6	0.4	1.1	0.8	1.8	0.4	1.2
Above 7000 ...	...	0.2	...	0.1	...	0.3	...	0.1

In comparison to the other oceanic bodies, the Atlantic Ocean has 53 per cent of the total bottom relief above 4000 m because of the extensive continental shelf of the Atlantic. Further, the major portions of all oceans lie between 4000-6000 m amounting to about 56.3 per cent of the oceanic surface of the earth. The areas below 6000 m are remarkably insignificant. Further, a more clear picture of the areas of oceans at various depths may be visualised from Table 3.¹

TABLE 3

Depth in fathoms	Atlantic Ocean Basin		Pacific Ocean Basin	
	Approximate area (sq. mile)	%	Approximate area (sq. mile)	%
0—500	9,948,000	23.8	4,861,000	7.0
500—1000	1,588,000	3.8	2,431,000	3.5
1000—2000	7,607,000	18.2	12,362,000	17.8
2000—3000	19,770,000	47.3	45,143,000	65.0
3000—4000	2,844,000	6.9	4,445,000	6.4
Above 4000	17,000	0.04	208,000	0.3
	41,814,000		69,450,000	

The Curve and the Isostatic Control. The nature of the hypsographic curve representing the height of land and the depths of the sea, can be explained when we consider the densities of the rocks which constitute them. This well-known curve clearly demonstrates the efficacy of isostatic control by assuming Airy's theory of isostatic compensation and density difference of continental and oceanic rocks. The density difference indicated by the abundance of silica, sodium and potassium,

¹ Beckinsale, *Land, Air and Sea*, p. 197.

THE DEPTH OF OCEAN

aluminium, silicates in the continental rocks having the average density of 2.72 to 2.81 gm. per cm^3 and the abundance of the iron, calcium and magnesium elements in oceanic rocks making the average density more than 2.81 gm. per cm^3 . The application of this concept proves the particular accentuated nature of the curve otherwise, "We shall have to presume that all the highest chains are today maintaining their altitude by unexhausted tangential compression, and the exceptional sagging of the oceanic deeps their depth by persistent tension, which is rather unlikely."¹

The importance of the Hypsometric or Hypsographic curve is great because it explains the co-relationship between the heights of the land and the depths of the oceans; and further it gives a zonal arrangement of oceanic bottom according to the various depths.

ZONES OF OCEAN BOTTOM ACCORDING TO DEPTH

(a) CONTINENTAL SHELF

Continents do not rise abruptly from the sea bottom, but there is a gradual rise of land specially in the upper part of the sea bottom. Hence wide and sometimes narrow but shallow land areas are found to be surrounding the main continental land. This transitional zone between the land and the actual sea bottom is known as the continental shelf.

The isobath line of 100 fathoms or 200 metres depth (though it can be 65 fathoms as well as 300 fathoms in occasional cases) demarcates the continental shelf area. In Table 4,² the bathymetric shelf (0-200m) according to Kossinna covers an area of 27.49 million km^2 or 7.6% of

TABLE 4

The Shelf-areas (0-200 m) of the Continents and Oceans respectively (10⁶km², according to Kossinna, 1921)

Continents	Areas	Oceans (excluding Mediterranean seas)	Mediterranean seas
Europe	3.11	Atlantic Ocean	4.59 of the Atlantic Ocean
Asia	9.38	Indian Ocean	2.37 of the Indian Ocean
Africa	1.28	Pacific Ocean	2.89 of the Pacific Ocean
Australia	2.70		
North America	6.74	Sum	9.85
South America	2.42		
Antarctic	0.36		
			Sum 17.64

Sum 25.99 + rather distant islands 1.50
Sum 27.49 $\times 10^6 \text{km}^2$, 7.6% of the sea surface.

¹ Du-Toit, Alex. L., *Our Wandering Continents*, p. 262.
² Defant, A., *Physical Oceanography*, p. 21.

the area of the ocean. This total area of continental shelf differs with the area of 30.6 million km² given by Wegener or with the area of 29.5 million km² given by Kegel. According to Table 4, the Atlantic Ocean with its extended inland seas has greater percentage of shelf area than other oceans.

The isobath line extends between the shoreline (low water tide line) and the continental slope of the oceanic bottom. Its seaward limit depends upon the change of slope and not on the certain isobath line and hence the width of the continental shelf varies considerably from place to place. The average width of the shelf for the whole world is about 30 miles, whereas Shepard has calculated the average width of the continental shelf to be 42 miles and the average depth 72 fathoms. Along the coasts of U. S. A., the continental shelf is 60-75 miles wide on the Atlantic side, whereas north of Cape Hatteras it is 150 miles wide but only 5-40 miles wide off the coast, north of New Guinea. The shelf is almost absent off the Provencal coast of France. An extensive shelf of 300 to 800 miles width and of 100 fathoms depth is found off the coast of the Arctic Sea. The Barents Sea shelf, 750 miles wide and 100-200 fathoms deep is supposed to be depressed under the load of glacial ice. It is scored by deep troughs which may be taken as an evidence of glacial action. Other wide shelves are in China Sea, Arafura Sea, North Adriatic Sea etc. The deepest shelves surround the Antarctic continent. Varying width of shelf is explained on the basis of the nature of coast, i.e. those coasts which have undergone glaciation have shelves of great width but full of irregularities, while those coasts having high mountainous chains along them have narrow shelves. Further, if there is a presence of Pseudo-continental shelf (area under the same depth but being separated due to the presence of deep water between the main shelf and itself), the continental shelves become all the more extensive.

The above survey brings out that the continental shelf in all covers about 8% of the total sea area whereas in individual oceans it covers 13.3% of the total area of the Atlantic Ocean, 5.7% of the Pacific Ocean and 4.2 % of the Indian Ocean. This fact is clearly attributed to the tectonic differences of the sea coasts and to the agents of erosion, e.g. folded and faulted coasts have narrow shelf whereas the shelf near river mouths is extensive. Further, another fact clearly brought forth by the diagrammatical representation of the variation of the elevation of continental shelf along selected latitudes is shown in Fig. 10. The major portion of the total shelf area is located between 50° and 85° N latitudes, whereas the continental shelf is less extensive between 40° N, and 45° S latitudes. And it is almost absent at about 25° S and 66° S latitude.

The average slope of the continental shelf is 2 fathoms per mile or 0.2 % or 17 feet per mile or 1°, but it varies from place to place due to the peculiar nature of the shelf and the surrounding continental masses. The shelves surrounding the glaciated part of the world are of gentle slope in comparison to the shelves of the coast where greater tectonic tension prevails or where the high areas of land surface are just adjacent to the great depth of the sea.

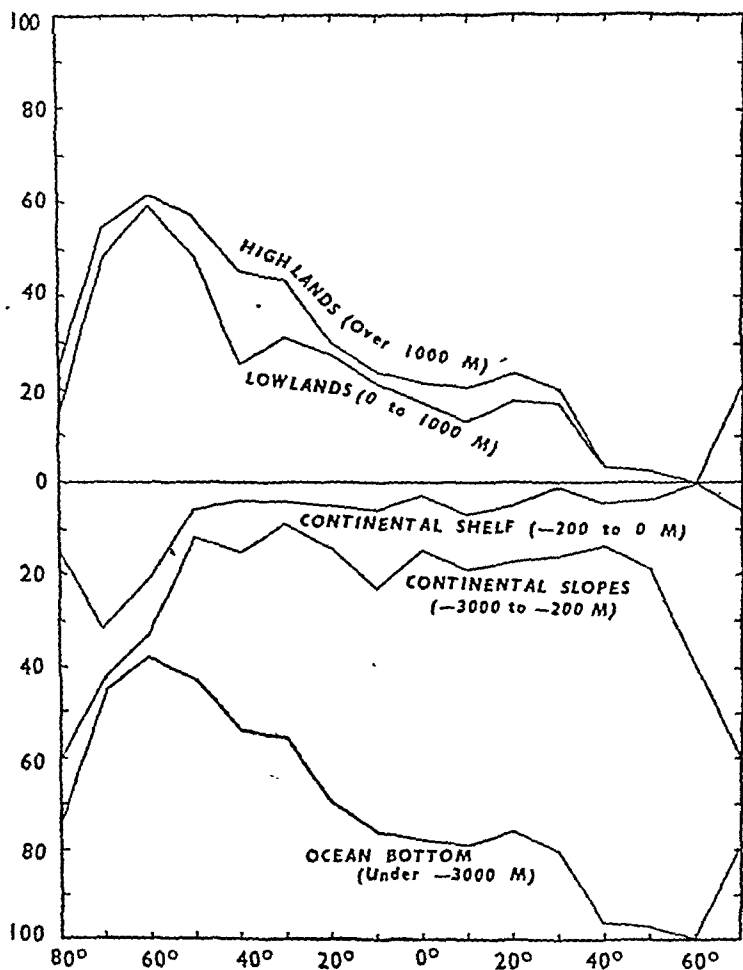


Fig. 10. Variation of elevation with latitude along selected parallels shown by percentage of profile.

Origin of the Continental Shelf. Due to vast varieties in the form and the nature of the continental shelves, various concepts have been put forth to explain their origin.

The classical theory, based on deduction alone, regarded the shelf as an extension of the continental platform. Hence the outer part was supposed to be formed by the consolidation of sediments by gradual deposition of material brought forth by rivers and waves. The inner part (the real shelf rock beneath the sediment), being composed of the rocks like those of the adjacent land, is an abrasion platform. On

prograding shores and where large rivers fall into the sea (North Gulf of Mexico coast), abrasion platform would be absent. But in its place constructional waves would proceed and form the continental shelf.

To conclude that all the shelves are formed thus would not be justified. The action of the waves to produce submarine platforms is restricted to some extent. So wide shelves, or partially enclosed continental shelves, are not possible by wave action. On the other hand, uneven relief of shelf cannot be explained only by delta formation. It can also be due to unequal erosion during Pleistocene lowering of the sea level. Again, objections arise when outcrops of crystalline rocks are found in the shelf, e.g., Palaeozoic rocks in English Channel, and granite in Californian Canyons.

Similarly, those who have tried to prove the origin of the shelf on the basis of a single thought have, no doubt, found evidences in certain areas, but they could not evolve a general pattern. Hence it proves that the origin of the shelf is not everywhere the same, i.e. in some regions it is a constructional form, whereas in others it is due to elevation of the submerged part.

In most of the areas the continental shelf is formed by constructive action. The deposition work is mainly done by the rivers for years and years. The assortment of sediment from coarse to fine is found on the shelf. The more calm the conditions prevailing in the sea, the wider will be the shelf by construction. Sometimes a sinking bottom of the shelf proves a place of abundant deposition. Experiment along such coast of eastern U. S. A. proves that the Appalachian rocks, which disappear under the Mesozoic and Tertiary rocks at the Fall line, are affected by a subsidence which lowers them to about 900 m. below the sea level at the mouth of Chesapeake Bay and to 3900 m. near the outer edge of the continental shelf. Again, recent investigations prove that Appalachians rise further seaward.

Similar conditions are found south of Nova Scotia and south of Grand Banks of Newfoundland. Here an excess of sediment on the shelf is found—ranging from the Cretaceous to the Quarternary age. Thus geosynclinal subsidence of such coasts is proved to be a definite fact. Gulf of Mexico coast is also of the same type, formed by 'sedimentation and subsidence' of Mississippi material. Though the coast along Congo reveals 2500-3000 m. thick Cretaceous and Tertiary sediment on the sloping surface, yet Veach maintains a complex evolution leading to folding, faulting and erosion in this area.

Apart from the above type of shelves, in certain regions flexures are found, without any sign of thick accumulation of sediment. This fact has been noted by Bourcart, Jensen and Umbgrove, whereas Vening Meinesz examined by the gravity measurements.

Further observations revealed positive anomalies off many coasts, and indicated two facts: firstly, the continents are formed of sedimentary rocks (sial) and the ocean bottoms of basic igneous rocks (sima); and secondly, there is a greater thickness of sima on the continental shelf itself. Due to this unequal distribution of sima and sial along the coast deep convection currents arise, which result in the periodical subsidence

of the land along the coast. The direction of movement is from sima, beneath the oceans, towards the continents of sial. For compensation, erosive material from the land is deposited over the ocean beds. Hence the general result is the rising of the continental areas and subsequent subsidence of the continental shelves.

Another explanation for this action is put forth by Jensen who assumes that a periodic cooling of the earth resulted in a marked shrinking under the oceans than under the continents. Hence sinking in oceans is found to give birth to the movement of material towards the continental border which is subsequently warped up. Such coasts are found off Angola coast of Africa. The number of flexuring would determine the character of the shelf. More phases of flexuring would result in deeply submerged shelves.

Continental shelves can also be formed by simple faulting or step faulting along the borderland. Such type of shelves are mostly found along mountainous areas as in Red Sea and along Queensland in Australia. If the down throw by faulting is less, then similar convection current from sima toward sial is postulated. If the throw is greater than 300 m. then the shelves would not be formed. According to P. Birot, the average width of the continental shelf along mountainous areas is 20 km.; thus a break in the continuity of the submarine relief is noted. Off Galicia, a depth of 200 m. is obtained only at a distance of 20-30 km. from the shore. Off the coast of Morocco, Bourcart found a series of gentle surfaces below 200 m., which progressively become steeper. Shepard's continental border lands are the areas of submerged plateaux and basins between 200-700 m, e.g., north-west of British Isles, north of Newfoundland, south-west of Formosa etc. Off the coast of W. India the shelf becomes almost nil.

Various examples have been put forth to justify the above fact, e.g. drowned (sub-aerially eroded) valleys in Adriatic, Sunda platform, New Guinea, West Brittany, the subsidence of land in Mesozoic and Tertiary period and the isostic effects associated with the glaciation (envisaged by H. Baulig).

Another explanation of the shelves was presented by M. Molte-dahl. It represents the fissured border of the continental shelves found along old rocks (shield areas) of Norway, Labrador and Greenland where uplift has occurred. In these areas, parallel depressions along the coasts are clearly marked. Along Norway the furrows are about 200 m. deep. These are later modified by glacial and fluvial actions, though the former action is not possible, firstly, because furrows are perpendicular to the glacial motion, and secondly, glacial actions are not found in certain areas (Californian coast) where such shelves are predominant.

Again, still another type of shelf is found along Algerian and Tunisian coast. Bourcart observed the occurrence of a series of folds or crests on the continental shelf. The deposition of sediments is found in the basins between the folds.

Besides the above ideas, other ideas are put forward for the origin of the shelves. According to Daly, the sea level was lowered by 38 fathoms during the Pleistocene period. Hence greater sea areas along

the margins of the continents were exposed. Now due to glacial erosion and deposition strange continental shelves evolved in these areas, when the sea regained its normal level. Such heavily glaciated, submerged trough like features are found along Norwegian shelf, whereas the shelf at Gulf of Maine at 180 m. reveals the occurrence of drumlins. Similarly, Hudson valley deepens the shelf by 50-70 m. deep depending on the force of the wind and the resistance of the rock to wave erosive activity which is also attributed to the formation of extensive platforms. By observations, wide shelves are found in calm areas.

Thus, in conclusion, it could be said that the origin of the continental shelf is still not explained fully. In various circumstances, the form of the shelf seems to adjust according to its environment. Again, to say that shelf is formed either by sea action or by land action only, is also a faulty statement. Continental shelf is a region where marine as well as continental influences have acted with the movement of the land (emergence and submergence).

(b) THE CONTINENTAL SLOPE

It is the area of steep slope extending just after the continental shelf up to a considerable depth from where a gentle sea plain takes its form. The extent of the slope area is usually between 200-2000 m depth though it covers a minor area of the total oceanic surfaces.

In the Hypsometric curve the slope seems to be greatly exaggerated in its angle, which is due to the general exaggeration of vertical heights in the diagram. The exact nature about the angle of the slope and its characteristics has come to be known due to the recent sonic soundings and the resulting vertical profiles. Shepard in 1941, basing his observations on such 500 profiles of different parts of the oceans, found that the continental slope off the mountainous coast has a gradient of 6% or 3°30' feet, whereas, off many wide well drained coastal plains, the angle of the slope is 3.5% or 2°2' feet only. The average slope for all the oceans comes to about 4°17 feet. Its nature and distance from the coast depends upon the topography of the land. In the Atlantic Ocean at 51°30' N, continental slope starts after a distance of 50 miles from the coast, and extends up to 240 miles up to a depth of 1000 fathoms. Here between 220-240 miles, the slope is measured to be 5¼%. On Calicut coast (India) the slope is between 5-15°. On Peru coasts, a depth of 50, 1000 and 2500 fathoms was found at a distance of 20, 90, and 200 miles respectively from the coast. Steep continental slope areas are found off the coast of Spain, St. Helena (40°), Tristan da Cunha (33½°) and St. Paul. The continental slope area occupies 8.5% of the total area of the oceans. In the Atlantic Ocean it is most significant, occupying 12.4% of the total surface of the Atlantic; in the Pacific Ocean, it occupies only 7.0% of the total area and in the Indian Ocean it covers 6.5% of the total area. Latitudinally, the greatest extent of the slope is on 80°N and 70°S latitudes, and between 20°N and 50°S latitudes.

The formation of the slope is attributed to the inability of wave action to extend further the eroded continental shelves. Continental slope is usually devoid of sea deposits due to its steep slope. The relief on

the slope areas are greatly a continuation of the land. A peculiar feature of great geological and geophysical interest is the presence of submarine canyons and trenches which also support the concept of agents of erosion for the formation of slopes in continuation to the shelf.

(c) THE DEEP SEA PLAIN

Forming the great flat plains of enormous extent from the slopes to the oceanic abysses, the deep sea plain covers the major portion of oceanic relief between the depth of 3000-6000 m. In all the oceans, the Deep Sea Plain areas cover about 75.9% of the total oceanic bottom areas, whereas, for the Atlantic Ocean as a whole, the deep plain areas occupy 54.9%; in the Pacific Ocean 83.3% and in the Indian Ocean 80.1%. This disparity between the Atlantic, the Pacific and the Indian Oceans can be accounted for by the presence of greater extent of continental shelf in the Atlantic in comparison to the Pacific and Indian Oceans. These vast plain areas are peculiar and we do not find such tracts on the land. On the other hand this vast stretch of sea plain is characterised by gentle and undisturbed relief. "It has been customary to emphasize this statement to the effect that if a trip by carriage on the bottom of the sea were possible, say from Brest to New York, the slopes encountered would be so gentle as to be unrecognized."¹ In this connection it would be more scientific to say that the gentle gradient does not mean that the relief and topography of the sea plain is featureless—the fact to be more elaborately sketched by further intensive deep sea soundings and detailed study of the beds of the individual oceans and seas. Further, the distribution of ocean bottom on latitudinal scale would also throw some light on its character. According to Fig. 9, the major part of sea plain is between 20°N to 60°S latitudes, whereas it is almost absent between 60-70°N latitudes, and it is overwhelmingly impressive at 60°S latitude.

The deep sea plain is covered with various oozes or pelagic deposits consisting of animal, plant and siliceous remains. It is practically free from the depositions and accretions done by agents of erosion.² The idea of complete flatness of the ocean floor was refuted by the Swedish Deep Sea Expedition, 'Albatross', which sailed from Goteborg in summer of 1947. During its 15 months voyage the scientists were astonished by the extreme ruggedness of the bottom of the ocean floor of the Atlantic and the Pacific. The only exception, however, was the Indian Ocean where south-east of Ceylon a level plain formed of hard lava extends for several hundred miles.

(d) THE DEEPS

This last zone is characterised by depressions in the ocean floor, deeper than the deep sea plain area. It covers only 7% of the sea bottom. In German it is known as *Tiefe* and in French it is *Fosse*. These Deeps are designated mostly after the names of the persons who discovered them but sometimes they are also named according to their geographical location. So far 57 deeps have been sounded. Out of the total, 32 are in the Pacific, 19 in the Atlantic, and 6 in the Indian Ocean.

¹ Marmer, H. A., *The Sea*, p. 109.

² Rachel, L. Carson, *The Sea Around Us*, p. 54.

TABLE 5
*The Principal Ocean Deeps*¹

Name	Locality	Area in sq. miles (thousands)	Greatest Depths (fathoms)
1. Valdivia	S. Atlantic and Indian Oceans	1,136	3134
2. Murray	Central N. Pacific	1,033	3540
3. Tuscarora or Japan	Off Japan	908	4655
4. Wharton or Sunda	Eastern Indian Ocean	883	3828
5. Nares or Porto Rico	Off W. Indian Islands	697	4662
6. Aldrich or Tonga	Central S. Pacific	613	5022
7. Swire or Phillipine	N. W. Pacific	550	4767
8. Tizard or Romanche	S. Atlantic	468	4030
9. Buchanan	E. of S. Atlantic Ridge	298	3063
10. Brooke	N. W. Pacific	282	3429
11. Moseley	N. Atlantic	279	3309
12. Bailey	N. W. Pacific	241	3432
13. Jeffrey	E. Indian Ocean	228	—
14. Belknap	Central Pacific	165	3337
15. Chun	N. Pacific	159	3318
16. Challenger or Marian	N. Pacific	129	5269

Further, by a survey of the location of these 57 deeps, a very interesting feature about the deeps can be visualized, that is, all the deeps lie near and parallel to the recent folds in the earth's crusts. They usually form very steep vertical descent of great magnitude from land to sea bottom. For example, the deep off Japan, of 4655 fathoms in the proximity of the Fusiya mountain of 12,400 feet height, makes a descent of 40,330 feet abruptly. Similarly, the Atacama deep on northern Chile coast and Llyllayaucu mountain along the coast makes a total descent of 46,704 feet.

¹ Jenkins, J. T., *A Text Book of Oceanography*, p. 22.

Chapter 4 SUBMARINE CANYONS

Recent technological expeditions have made possible for us to know in detail the morphology of the ocean basin and shelves which reveal strange features in the form of submarine canyons¹ and troughs. These canyons, mostly resembling the land valleys, are carved on continental shelves. Investigators have found two types of canyons: the glacial and the non-glacial. The former is a wide trough-like canyon, eroded and carved by glaciers only. These are often found on the Norwegian coast and also on the Arctic shelf. The latter is a deep elongated furrow entrenched in the shelf by some agencies other than the glaciers. The non-glaciated submarine canyons excel in numbers, hence their distribution and the problem of origin are widely studied.

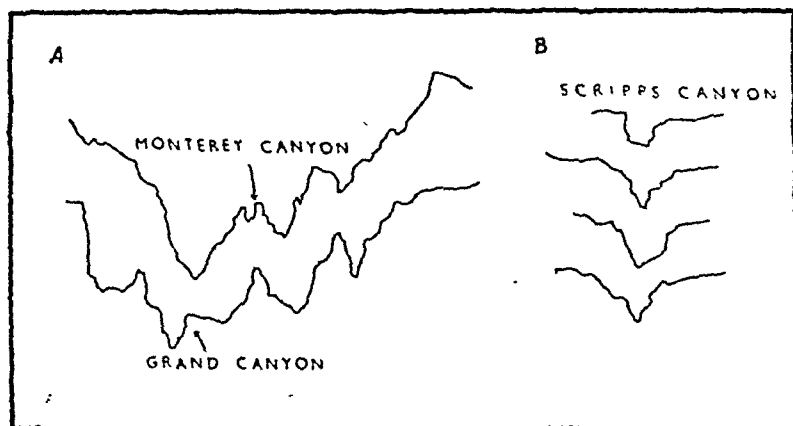


Fig. 11. (A) Transverse profile of submarine canyon in Monterey Bay compared to a profile of the Grand Canyon of Colorado in Arizona.

(B) Transverse profile of a small, steep-walled canyon off the southern California coast. (After Shepard, 1938).

The non-glacial submarine canyons are found to be located on the shelf and slopes of the continental platforms. The head of the canyon, excepting few trenches which are found parallel to the land, usually points towards the coast and starts at the beach-head or one or two miles ahead of the shore line. The deep trench measures one to several miles in width on the top. The course of the canyon is traceable up to 10 miles usually

¹ Only non-glacial submarine canyons are dealt in this chapter.

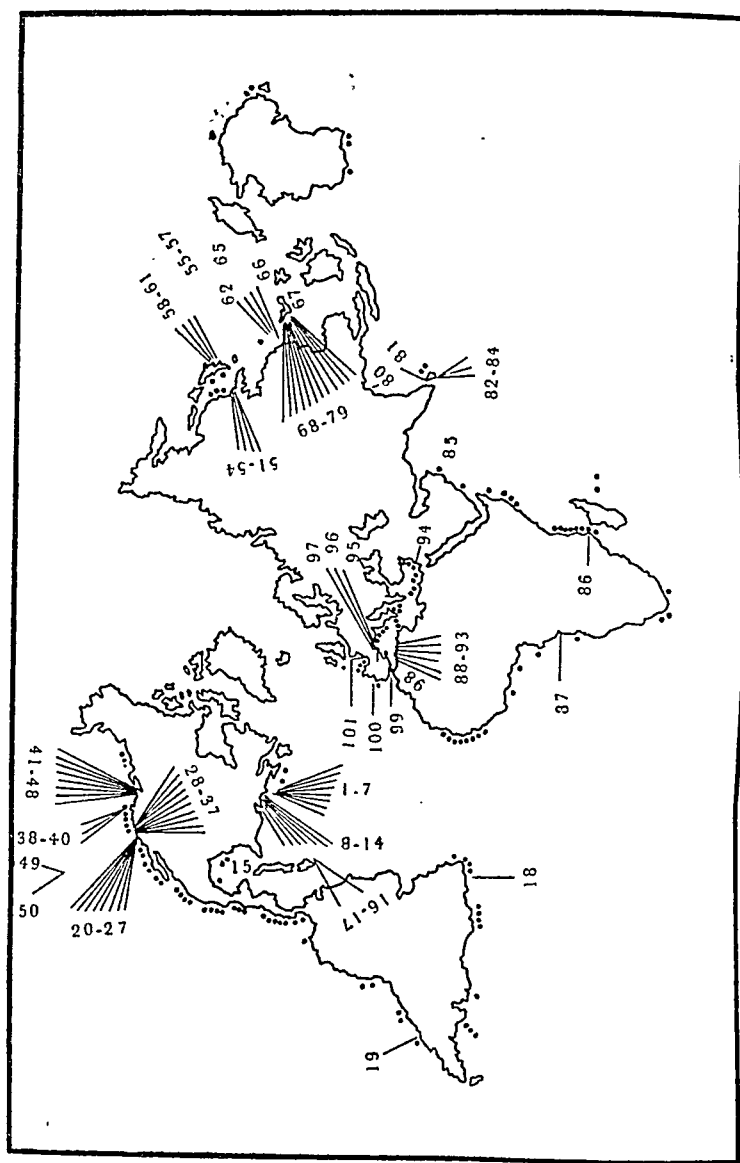


Fig. 12. World distribution of Submarine Canyons. Numbers given where canyons have been named and where sufficient soundings for longitudinal profiles were available. Table 1 identifies those canyons by name. Dots show location of other canyons, some of doubtful character. Submarine depressions of probable glacial diastrophic origin are omitted.

(By permission, from *The Geographical Review*, N.Y.)

TABLE 1. Per Cent Grade of Canyons

EASTERN COAST OF THE UNITED STATES

WESTERN COAST OF THE UNITED STATES

COMBES OF EASTERN ASIA

NAME	MEAN	LAT.	LONG.	NAME	MEAN	LAT.	LONG.	NAME	MEAN	LAT.	LONG.
1 Corsair	6-0	41°26' N	66°14' W	20 La Jolla	7-4	32°51' N	112°01' W	51 Subokun	5-1	41°33' N	129°40' E
2 Georges	10-2	41°16' N	66°16' W	21 Scripps	7-4	32°54' N	112°16' W	52 Yan To	7-0	40°42' N	128°29' E
3 Atlantic	9-1	41°17' N	66°26' W	22 Oceanside	4-8	33°07' N	117°21' W	53 Oryn	10-7	38°20' N	128°4' E
4 Lydonia	4-5	40°32' N	67°44' W	23 Catalina	7-7	33°23' N	118°29' W	54 Pisen Chyang	8-5	38°15' N	128°38' E
5 Gilbert	4-7	40°23' N	67°55' W	24 Newport	6-3	33°36' N	117°55' W	55 Hojezu	5-4	36°48' N	137°05' E
6 Oceanographer	4-2	40°29' N	68°10' W	25 Redondo	3-6	33°50' N	118°23' W	56 Yokata	10-0	36°46' N	137°11' E
7 Hydrographer	5-0	40°13' N	69°07' W	26 Dume	12-5	33°57' N	118°49' W	57 Jinzu	8-4	36°46' N	137°13' E
8 Fire Island	5-3	39°32' N	72°05' W	27 Mugu	6-4	34°05' N	119°07' W	58 Sagami	2-7	35°15' N	138°11' E
9 Hudson	2-7	39°41' N	72°29' W	28 Arguello	2-9	34°38' N	120°48' W	59 Uraga	2-6	35°14' N	139°46' E
10 Manassquan	6-3	39°13' N	72°28' W	29 La Cruz	3-4	35°43' N	121°25' W	60 Suruga	3-4	35°08' N	138°43' E
11 Meteleconk	6-2	39°12' N	72°31' W	30 Villa	4-1	35°49' N	121°28' W	61 Sino Saki	5-1	34°55' N	139°46' E
12 Toms River	6-1	39°10' N	72°42' W	31 Plakett	4-4	35°55' N	121°31' W	62 Chotsui Pii	19-0	23°31' N	121°30' E
13 Delaware	3-8	38°30' N	73°30' W	32 Lucia	2-9	36°03' N	121°37' W	63 Ocho Pii	11-7	23°13' N	121°25' E
14 Chesapeake	2-6	37°30' N	74°31' W	33 Parlington	3-4	36°10' N	121°43' W	64 Torela	13-8	23°02' N	121°20' E
AVERAGE	5-5			34 Mill Creek	4-4	35°58' N	121°31' W	65 Tan Kan	1-9	22°24' N	120°23' E
				35 Sur	3-0	36°16' N	121°54' W	66 Batulinao	2-3	18°22' N	122°02' E
THE MEDITERRANEAN				36 Carmel	7-6	36°32' N	121°56' W	67 Cagayan	2-4	18°23' N	121°37' E
				37 Monterey	2-9	37°48' N	121°47' W	68 Bagayra	10-0	18°18' N	120°28' E
				38 Delgada	5-5	40°07' N	124°47' W	69 Novotas	8-5	18°17' N	120°28' E
				39 Mattole	4-9	40°17' N	124°21' W	70 Laoag	7-2	17°13' N	120°27' E
				40 Mendocino	8-2	40°22' N	124°25' W	71 Abra	4-9	17°29' N	120°25' E
				41 Columbia	2-0	46°16' N	124°20' W	72 Santa	8-8	17°24' N	120°27' E
				42 Willapa	2-3	46°35' N	124°29' W	73 Mainganny	5-5	16°56' N	120°35' E
				43 Guide	2-6	46°34' N	124°39' W	74 Amburayan	8-4	15°16' N	128°00' E
				44 Chehalis	2-5	46°57' N	124°49' W	75 Bucas	10-5	15°11' N	119°57' E
				45 Quanaht	4-2	47°18' N	124°45' W	76 Panan	9-3	15°05' N	119°57' E
				46 Fraser	1-9	48°04' N	125°17' W	77 Santo Tomas	10-5	14°57' N	120°01' E
				47 Niziat	2-5	48°13' N	125°42' W	78 Pamatuan	3-8	14°16' N	120°29' E
				48 Barklay	3-3	48°22' N	125°58' W	79 Manila	7-0		
				AVERAGE	4-83			AVERAGE			
OCEANIC ISLANDS				INDIAN OCEAN PROVINCE				INDIAN OCEAN PROVINCE			
NAME	MEAN	LAT.	LONG.	NAME	MEAN	LAT.	LONG.	NAME	MEAN	LAT.	LONG.
88 Selef	11-0	36°19' N	3°33' E	87 Congo	1-1	6°01' S	12°35' E	81 Trincomalee	12-7	8°30' N	81°14' E
89 Sebori	19-0	36°55' N	3°52' E	85 Indus	1-0	23°45' N	67°35' E	82 Kumbukkan	9-0	6°23' N	81°44' E
90 Axin	11-0	37°02' N	7°34' E	80 Ganges	-8	21°27' N	89°41' E	83 Nilwala	15-9	5°54' N	80°32' E
91 Nil	15-0	36°54' N	5°58' E	15 Mississippi	1-1	28°40' N	90°03' W	84 Panadure	5-9	6°40' N	79°46' E
92 Zhou	10-0	36°58' N	6°12' E	9 Hudson	2-7	39°41' N	72°29' W	86 Mocambo	5-8	15°08' S	40°37' E
93 Tamarant	16-0	37°04' N	6°32' E	41 Columbia	2-0	46°16' N	124°20' W	AVERAGE	9-8		
94 Sanik	11-0	33°33' N	35°20' E	101 Cap Breton	1-9	43°39' N	1°28' W				
95 Arna	12-0	43°47' N	7°54' E	100 Nazare	2-7	39°35' N	9°06' W				
96 Roja	11-0	43°45' N	7°39' E	14 Chesapeake	2-6	37°30' N	74°31' W				
97 Marselle	7-6	43°20' N	5°19' E	AVERAGE	1-7						
98 Lobregat	3-7	41°16' N	2°11' E								
99 Gibraltar	3-5	36°09' N	5°24' W								
AVERAGE	10-9										
-49 Kalliu	21-2	22°15' N	159°37' W								
50 Honopu	19-2	22°11' N	159°41' W								
17 Maneyes	6-6	18°27' N	65°43' W								
16 Pihones	8-4	18°28' N	65°57' W								
AVERAGE	13-8										

into the sea. Further, the different continental shelves record varying slope of the canyons, the average slope being 1.7%. Those which are in front of river mouths are usually long (as Congo canyon) and less steep. But the canyons found along the islands have steepest profiles with 13.8% slope. The depth of the floor is found up to 2000-3000 feet or even more below the sea level. "Most of these are found deeper than the Yellow Stone Canyon, and the greater must be comparable with the Grand Canyon or the Colorado...."¹

The sides of the valley mostly remain steep and precipitous like canyon walls, because they cut through the solid igneous or sedimentary rocks² of the shelf. Shepard observes that these canyons are similar to youthful river cut valleys generally V-shaped in cross section and sinuous in course. But they are much steeper than sub-aerial valleys excepting in the mountainous region. Many of these canyons have dendritic pattern of tributaries resembling a land valley. However, Kuenen and Crowell have emphasised certain differences between canyons and the sub-aerial valleys. They did not find winding canyons or meanders of small radius while on the other hand their straight course is observed.

The longitudinal profile does not show greater irregularities than the sub-aerial valleys. At various places the break of slopes is observed, though reversal of slope is not found. This profile is usually steeper than the land valleys. According to Shepard and Beard, the average profiles of 102 world canyons in the upper, lower and middle sections are 11.62%, 4.76%, and 6.63% respectively. In their lower section they have an appearance of hummocky topography with depressions and elevations on the surface.

Various types of oceanic deposits are also found in these submarine canyons. The steep walls of the canyons are generally free from unconsolidated sediment. The deposits in the bottom of the canyons are generally coarser than those on the adjacent shelves. In some of them, cobbles and gravels have been found, though deposits of sand, clay, and silt are also widespread.

The slope of the upper part of the valley is conterminous with that of the shelf, but the gradient of the valley varies according to the force of the erosion and the character of the shelf, usually gentle in the beginning and deeper later on.

DISTRIBUTION OF SUBMARINE CANYONS

A world-wide investigation of soundings on the shelves led Francis Shepard and Charles Beard to calculate the existence of 102 canyons in the world as shown in Fig. 12.³ The names of these are either related to the rivers, in front of which they are located, or after the names of the expedition vessel or coasts.

Before going into the details about the distribution of canyons, certain facts relating to their location must be viewed.

¹ Shepard, F. P., "Submarine Valleys", *Geographic Review*, Vol. 23, 1933.

² Monterey canyon off the Californian coast is cut into granite that is overlain by sedimentary rock.

³ *Geographical Review*, Vol. 28, 1938, p. 440.

(i) Canyons are found either in front of the large rivers or near the localities where rivers existed in the remote past.

(ii) They are also related to the small rivers on the land. Sometimes such submarine canyons are comparatively deeper and extensive than those found near big river mouths.

(iii) Submarine valleys often characterise relatively straight coasts rather than deeply indented coast lines.

(iv) Latitude is in no way a bar to the development of submarine canyons. They are universal in nature and appearance.

(v) Canyons are equally found off the stable coasts as off the coasts where Quaternary and Tertiary movements have taken place.

In general it could be said that they are numerous off the east coast of U. S. A. from Canada to Cape Hatteras, off the Californian and Mexican coast and off the North Mediterranean, Philippine, Japan, Aleutian islands etc.

Submarine Canyons in the Atlantic. The Atlantic Ocean is particularly known for the existence of some of the great canyons. Several decades ago Hull and Spencer marked the extension of the valleys of the Atlantic rivers of United States over the shelf. During 1930 Corsan Gorge was discovered on George's bank, in an expedition launched as a result of break in the cables, following the earthquake of 18th November, 1929. In 1931, several other canyons were discovered in this section of the Atlantic. St. Lawrence trough was connected with the St. Lawrence river, and the Cabot trench was found west and south of the Newfoundland island. However, one feature was marked throughout that the canyons were too steep, indicating the canyon carving through the solid rock of the continental shelf rather than through the soft limestone of the ocean floor.

Hudson canyon off the Atlantic coast of United States in front of the mouth of Hudson is traceable across the shelf, even up to the mouth of the river. The canyon takes its origin in the form of a deep channel, near Sandy Hook and extends for about 93 miles. At the head it is one mile wide whereas 50 miles downwards it widens to 5 or 6 miles. The depth of the canyon is estimated to be 3700 feet. Just south of this, there is another submarine canyon in front of Chesapeake Bay. Chesapeake canyon and Hudson canyon have lowest gradient among all the canyons off the east coast of U. S. A. Average gradient of the canyons here is about 5% while the degree of difference is slight. The steepest gradient profile found here is about 10%. When considering the difference of the gradient in a single canyon, one finds that Atlantic canyons, as shown in Fig. 14, have steeper gradient on the other sides than in the centre.¹ One exception is found in Chesapeake canyon which exhibits lower gradient on the outer part.

In spite of the occurrence of so many submarine canyons, the coast of U.S.A. has been remarkably stable since Mesozoic era; only recently there are few indications of submergence at the rate of 2 feet per century.

¹ Those who compare submarine canyons to river valleys will find difference in the river and canyon profile. The former is gentler towards the end, whereas the latter has steeper gradient at its outer margin.

In the Gulf of Mexico, Mississippi trough penetrates 22 miles in the gulf coastal shelf, the average gradient being 1%. On the Carib-

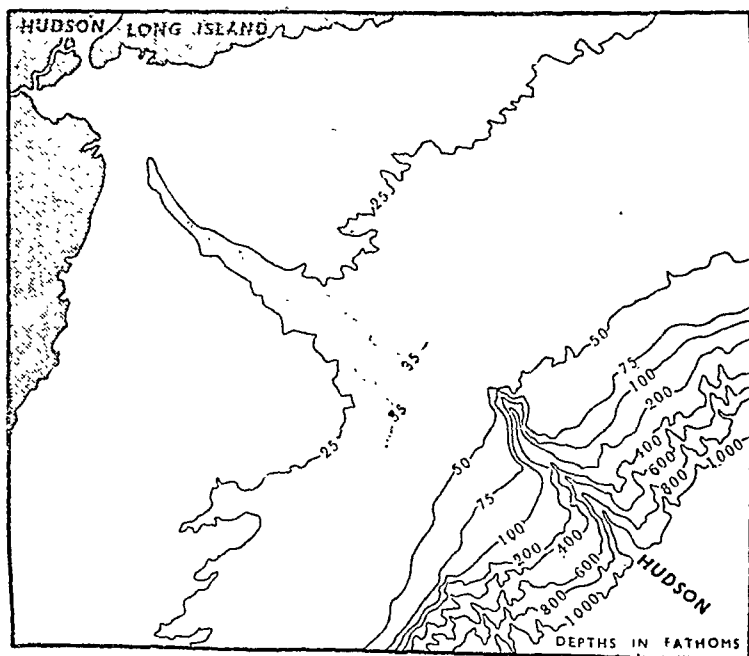


Fig. 13 Hudson Canyon.

(By permission of the publisher, from H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans: Their Physics, Chemistry and Biology*. (C) 1942. Prentice-Hall, Inc., U. S. A.)

bean coast of Panama near the Costa Rican boundary, four V-shaped canyons are notched in the edge of the continental shelf. Two are associated with large rivers like Sixaola and Changuinola, whereas the other two are in front of two entrances to Almirante Bay known as Boca del Drago and Bocas del Toro. The former canyons are 500 fathoms deep with their heads close to 30 fathom contour line near the coast. There was a shallow channel in between the canyon and the coast, which has been filled by wave and current action. All these canyons have V-shaped profile and 10% seaward gradient.¹

On the western continental shelf of the European continent many submarine canyons are found. The most important one is Fosse de Cape Breton canyon, as shown in Fig. 15.² It lies on the floor of the Bay of Biscay, near the coast of south-western France. The canyon is in front of an old 15th century mouth of river Adour. Near the present embouchure the channel is about 175 fathoms deep or 117 fathoms below the platform in which it is cut. Further, seawards it becomes a

¹ Terry, R. A., "Notes on Submarine Valleys off the Panamanian Coast," *Geographical Review*, Vol. 31, 1941.

² Monkhouse, F. J., *The Principles of Physical Geography*, p. 228.

'true canyon 4000 to 6000 feet deep and finally it opens out at the foot of the continental slope at some 9000 feet below the present sea level. The south side of the canyon is ravined, as if by tributary streams.'¹ According to Shepard, Cape Breton canyon penetrates 30 miles into the shelf.

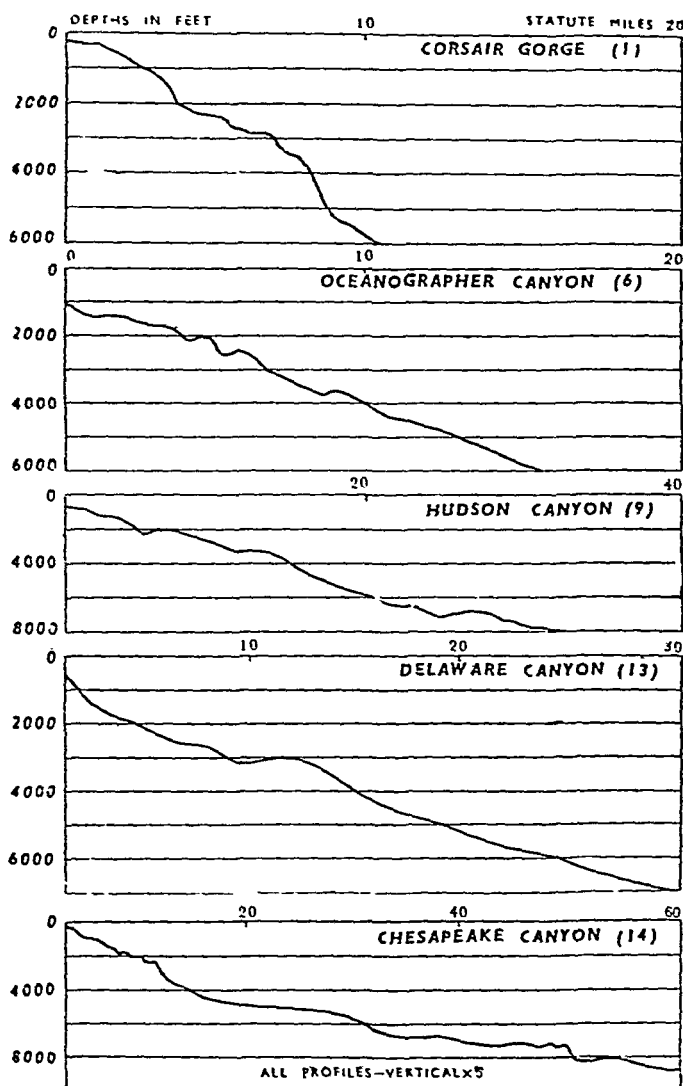


Fig. 14 Longitudinal profiles of canyons off the eastern U. S. A. Numbers after names of canyons correspond to those on Fig. 12 and Table I

(By permission from *The Geographical Review*, N. Y.)

¹ Steers, J. A., *The Unstable Earth*, p. 54.

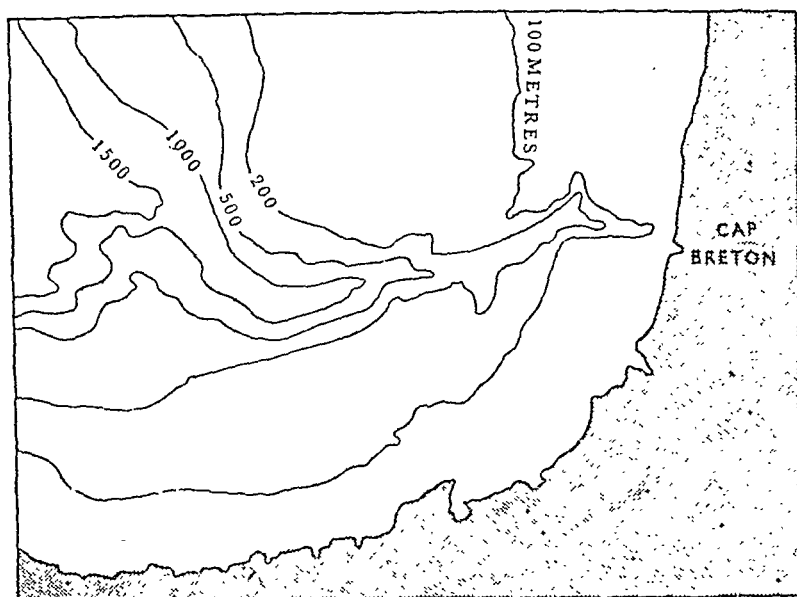


Fig. 15. The Fosse de Cap Breton canyon, off the coast of south-western France.
(By permission, from *The Principles of Physical Geography* by F.J. Monkhouse.
Copyright 1954. University of London Press Ltd.)

A similar phenomenon is also traceable off the river Gironde in France, and near the coast of Portugal and Spain. Nazare canyon on the western coast of Portugal reminds of the old mouth of Tagus river. In its deepest part it is 4000 m (2190 fathoms) deep. At 5 places the depth is recorded near about 5 miles. This canyon is perhaps the best sounded canyon on the Portuguese coast and appears just near it. Further, it extends for about 50 miles on the continental shelf. Some 10 or 12 miles from the coast two islands of granitic and gneissic rock, named Berlengas and Faralhoes, project from the continental shelf close to the southern rim of the canyons. The canyon was first discovered by Hull, and classified by Shepard under the heading of 'Canyons sfound off the mouths of large rivers'. Andrade,¹ during his investigation along the Portuguese coast found that this canyon consists of a series of graven like valleys.

In the Atlantic, canyons are found off Gold Coast, in front of Niger and Ogowe rivers. Congo canyon, as shown in Fig. 16², near the mouth of Congo river is traceable up to 95 miles. At the head of the canyon the width of the gully is 3 miles and its depth is 333 fathoms. After 35 miles the width of the canyon is 6 miles and the floor of the gully is 6000 feet below the level of the plateau in which it is carved. The canyon

¹ Carlos Freire De Andrade, 'Submarine Canyons off the Portuguese Coast, *Geographical Review*, Vol. 30, p. 521.

² *Geographical Review*, Vol. 23, 1933, p. 84.

has stable bottom and penetrates deep into the shelf. Among the inland seas of the Atlantic, the Mediterranean has canyons² off the coast of Syria and French Riviera, the average slope being 10%.

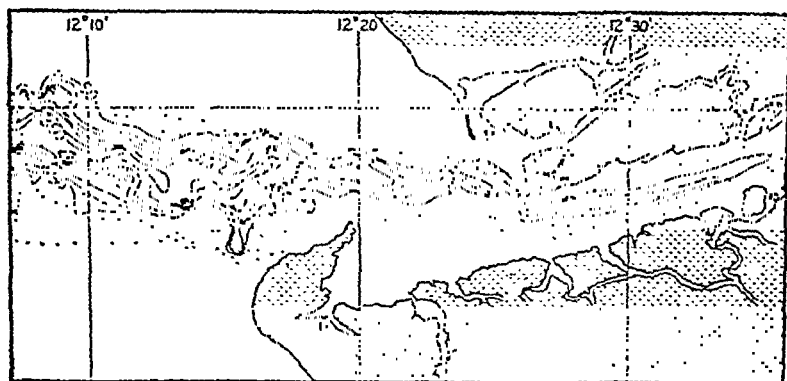


Fig. 16. The inner portion of the Congo trench showing how the depression enters the estuary at the mouth of the Congo river. Each dot of the water area represents a sounding.

(By permission, from 'The Geographical Review', N. Y.)

Submarine Canyons in the Pacific. In the Pacific Ocean, on the western side of America, a few canyons are found off Vancouver and Aleutian islands. Columbia canyon penetrates 12 miles into the shelf. Out of the 29 canyons noticed by Shepard off the west coast of U. S. A., most of them are near the Californian coast. Monterey canyon (Fig. 17)¹ near the Californian coast is situated at the former outlet of Salinas River, 70 miles south of the Golden gate. The canyon was first recorded in 1897 up to 18 miles off the coast and with 800 fathoms depth. Later on in 1914, the valley contours were surveyed and extended up to 3200 m. (1700 fathoms) and 70 miles further from the shore. It was only when echo-soundings were practised in 1928 that details of the submarine valley were traced up to 2000 fathoms, about 65 miles off the shore. Recently in 1932, Coast and Geodetic Survey have showed a descent in the valley profile from 500 fathoms at a distance of 15 nautical miles at the head of the valley, down to 1900 fathoms, as far as for 65 miles. Monterey Bay is a wide trough which includes many submarine canyons like Ascension canyon, Soquel canyon, Carmel canyon and Monterey canyon, which extend like tributaries to the Monterey canyon.

The axis of the Monterey canyon is winding and its head is almost on the beach. After a course of about 50 miles it enters, at about 1500 fathoms, a trough of different character from the inner one—the inner V-shaped giving place to a much flatter cross section, known as Monterey trough. The Pacific canyons have steeper gradient due to coarse sediment available at the head. Carmel canyon records 30%

¹ Benjamin, Howell, *Introduction to Geophysics*, p. 273.

gradient. Its bottom is composed of coarse sand and gravel, which usually needs dredging. The occurrence of granite was found in Monterey Bay at 500 fathoms, and Pliocene sediment at lesser depths. Here also coarse gravel sand and silt was dredged from the bottom of the valley.

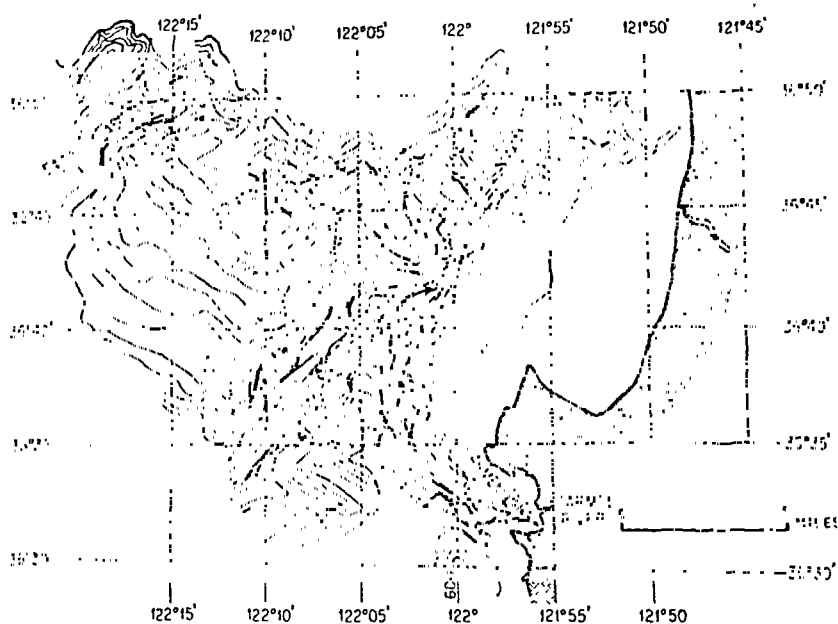


Fig. 17. Monterey submarine canyon, California. (After Shepard, 1938.)

(By permission, from *Introduction to Geophysics*, by Benjamin F. Howell, Jr. Copyright 1959, McGraw-Hill Book Company, Inc., N. Y.)

Other canyons off the Californian coast are Mugu, Scripps, and Dume. Arguello is also one of the largest American submarine canyons, traceable for 70 miles. It shows the steepening just after 26 miles from the head, between 6000 and 8000 feet. Davidson points out that various submarine canyons 200-300 fathoms deep are found off Santa Monica coast. Pitter has found another canyon named Vincente submarine valley 15 miles south of Santa Monica. The average gradient of the Californian coast is 4.8%. This is comparatively gentler than that of the canyon on the eastern coast as gradient is related to the slope of the shelf and not to the width of the shelf. Generally west coast canyons have steeper inner ends than the average gradient. It shows steepening of gradient from 6000 feet off the coast. Carmel, Mugu, Scripps and Dume canyons have maximum gradient of 30, 24, 21 and 21 per cent respectively. This steep gradient is attributed to the deposition of sediment.

South of these submarine canyons along the coasts of Mexico, Central America and off the western coast of Panama, a submarine canyon is traced which starts at 20 fathoms contour near the northern end of

Pearl island at the mouth of Bayano river. The canyon extends for about 80 miles towards the south up to 400 fathoms (Fig. 18). Many channels bifurcate from this and suggest its similarity to a delta. But the valley between 100-200 fathoms is not more than half as steep as those on the Caribbean side. The cross profile is broad and flat up to 100 fathom line and shows the maturity of the upper part of the canyon. At the mouth of the drainage of Darien province, in front of debouchure of the gulf of San Mignel, similar valleys are found. But the canyon is not lower than 40 fathoms and it extends to the east Bayano notch for about 70 miles, up to 400 fathoms. The edge of the shelf along the coast is at places 6000 feet high, thus offering a favourable situation for submarine canyons. But the valley between 100-200 fathoms is not

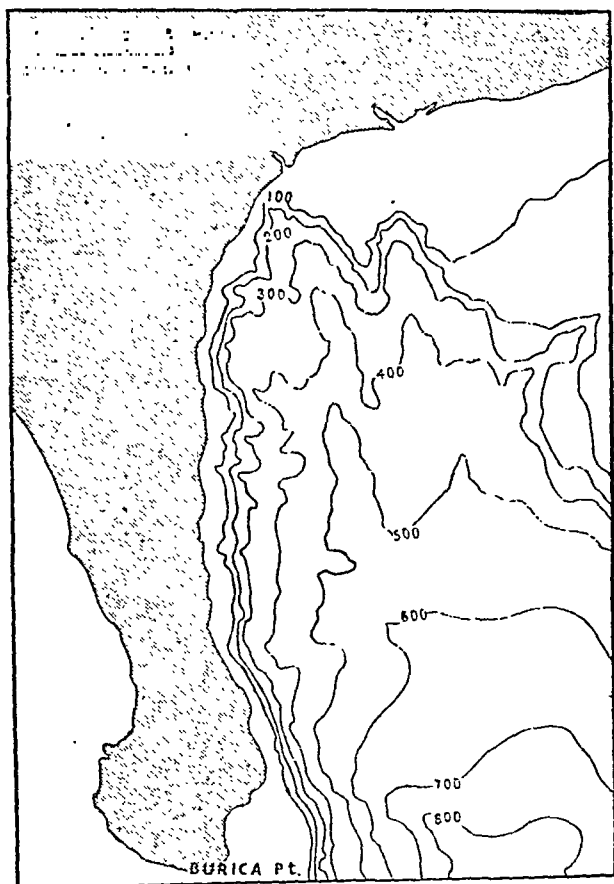


Fig. 18. Panama Submarine Canyon.

(By permission from, *The Geographical Review*, New York, Vo. 31, 1941).

steep and the cross profile is broad and flat up to 100 fathoms. Again, radiating channels suggest a delta-like development.

Canyons found off Burica peninsula are regarded among the largest submarine valleys of Panama. South of this peninsula, in David Bay, a canyon is found. The valley is also V-shaped but the bottom is comparatively flat. It runs for 10 miles along the peninsula, up to the depth of 1000 fathoms and is 30 miles long. One such valley is found near Esmeraldas river of the Ecuador.

On the eastern coast of Asia canyons are found off Honshu island, in Saganin Bay and Tsuruga Bay. In Fiseu Chyang canyon off the coast of Korea, the head has comparatively steeper gradient whereas the outer portion is flattened. The average gradient is 24.8%. Off the coast of Formosa many irregular canyons are marked. Philippine canyons are on the main coast of Luzon. In front of Cagayan river a gentle gradient canyon is found which has concave upward curve. In other canyons like Saganin, and Chotsiu Fii, steepening of the valleys takes place at 8400 feet and 6000 feet respectively after a slight gradient. Fii canyon has an average gradient of 43%. Various other canyons are also found near Hawaiian coast. Generally, east Asian canyons show higher gradient than those found on U. S. coast. The former have 7% gradient in the outer portion and 14.4% at the head.

Submarine Canyons in the Indian Ocean. Canyons are found in the Indian Ocean near the mouth of Ganges and Indus rivers. Ganges canyon has an average gradient of 0.8%. Several other submarine canyons are also found in north-east of Ceylon, which show 60% of slope at the head due to steeper continental shelf. On the eastern coast of Africa, and south of Zanzibar these canyons possess 9.8% gradient.

Canyons of less certain character are also found in various parts of Mediterranean, Brazilian coast south of cape San Roque, west coast of Mexico and Africa. There are valleyless continental shelves as given by Shepard¹: (i) East coast of U. S. A., south of Cape Hatteras; (ii) West coast of U. S. A. from Cape Mendocino to Columbia river; (iii) East coast of Asia, off the Yellow Sea and Gulf of Siam, and coasts of Australia; (iv) South coast of Asia in Gulf of Martaban; (v) Off the western coast of India, south of Indus river; and (vi) Glaciated regions where trough shaped valleys are found.

Many explanations have been put forth regarding the marked absence of the submarine canyons on some of the continental shelves. Such areas, in spite of having deep valleys on the land, do not exhibit any sign of canyons. Those who advocate that the sliding of land had been a continuous process beneath the sea level have no doubts that canyons were cut into these shelves but were filled and blotted out due to river borne sediment and land sliding. According to them in places where the continental slopes and shelves are gentle or terraced, the sediment has less impetus to slide, but on the contrary it deposits along the valleys, and when the valleys are filled, they are rapidly cemented

¹ Shepard, F. P., 'Submarine Valleys', *Geographical Review*, Vol. 23, 1933, p. 88.

and this prevents future land sliding.¹ Land sliding is accelerated in the earthquake areas.

At some places the current running along the slope may wear back the spurs between valleys, until the slopes are equalised, as it is found on the south-east coast of U. S. A.—south of Cape Hatteras. Here the shelf is terraced and underlies the Gulf Stream. Valley free areas of Yellow Sea and Martaban Bay indicate the gentle continental slopes preventing the occurrence of valleys.

ORIGIN OF SUBMARINE CANYONS

Diastrophism. The idea of relating the origin of submarine canyons to the earth movement presents varying conditions in which the canyons originate, i.e. faulting along a plane produces a fault trough or a graben between rift blocks, the warping produces broad synclinal basins and steep fold forms a synclinal trough. The idea of diastrophism was just accepted by a Portuguese writer, and was advanced by Andrade who states that the canyons consist of a series of graben like valleys formed during very gradual local coastal displacement. The discontinuous sections of the canyon are explained by unusual deposition in the graben. Their absence on the mainland is attributed to the sub-aerial erosion, whereas the submarine part is well protected under water. No doubt there is difficulty in explaining the unequal deposition of the debris in some parts due to which a few channels are obliterated even under the sea water.

Lawson has mentioned one such tectonic canyon off the coast of California. De la Roche Ponie also referred to a similar valley near the coast of Cyprus and Morocco. J. W. Gregory even listed Hudson and St. Lawrence troughs in this type. Yanasaki of Japan has also stressed the importance of diastrophism in canyon formation in Japan.

According to Jensen and Bourcart the continental border is a zone of flexure. Due to the unequal distribution of sial and sima just along the coast, a sub-surface convection current would result from the sea to the land. Thus the land would rise up with a subsequent erosion of the surface and the sea bottom would subside. Jensen believes that due to periodic cooling of the earth, the sea bottom contracts more than the land surface, hence the former subsides and sends convection currents towards the land which is subsequently uplifted. Thus Bourcart maintains that canyons are Quarternary river valleys which subsided due to recent continental marginal flexure. Hence the longitudinal profile of the canyon becomes steeper than the sub-aerial valley profile. If multiple flexures occur then stepped profile of the canyon would be found, such as it is found in the lower Congo Canyon. Jensen thinks that long continued flexures have occurred in the Congo Canyon.

Thus explanation of changes in the level is afforded by giving the process of the floor sinking and the resultant movements. Sedimentation just beyond the shelf causes a sinking of the sloping floor, while erosion causes the land to rise, hence the shelf region on the whole develops an oceanward tilt and occasional slumping in such areas. Such evidences

¹ Examples are afforded by coasts of W. Florida, N. W. Australia, and S. India.

are afforded by African coast, along Congo. "It is significant," says Du Toit, "that these canyons which should not have been formed, should not be so finally developed on the Congo shelf, that is regarded as disjunctive." Jensen also regards the Congo gorge as a result of this down warping while others mention that steep faults are clearly visible in some of the tributary valleys, though few have concealed them due to deposition of sediment. On the Gulf of Panama side, fault channels mark tributary development during the recession of the Pleistocene sea level. In Burica Bay also the topography indicates submergence to south west. A dissected peneplain on the west is tilted to the eastern side. This region is also seismically active, and it is understood that depression was formed due to the volcanic eruption of El Baru at the head of the canyon. Contrary to this, the canyon on the shelf seems to be an eroded valley.

Observations in Bayano canyon exhibit steep cliffs on the eastern side of the lower part, suggesting fault scarp. For all of them there was only one explanation and that of faulting or diastrophism. Hull advanced the view that an enormous depression of the land must have occurred. It is, however, suggested that the strips of the floor bordering the Atlantic coasts characterised by such gorges are merely marginal parts of the continent that have depressed through down warping and down faulting during stretching of the Atlantic rift basin and that they constitute unstable fringes in process of being torn off from the continental blocks as that basin continues to deepen and widen. These gorges would in short represent ricks sliced by the rivers through the fault line scarps before and while the down-dragging in question took place.

Further evidences of subsidence are afforded by the severe earthquake of 18th November, 1929, near Newfoundland coast where according to Gregory cables were broken on either side of Cabot strait, and coastal shelf near Maine subsided. Following summers, Corsair gorge was found. Gregory states that the breaks in the cables were due to the renewed subsidence of the floor, or faulting along the parallel series of fissures. "The fractures were not a single pair of faults, but were probably on two sets of faults each set along one side of this great submarine rift valley."¹

Those who criticise the diastrophic explanations suggest that faulting and rifting is only possible on a few shelves and not on all. The explanation of canyons may seem easier in the regions where earth movements have occurred in Tertiary-Quaternary period as in the Pacific or the Mediterranean. But it seems impossible in regions like the Atlantic coasts where no recent movement is seen and the canyons are found to cut through the most recent sediment—the Pliocene rocks. Hence it proves that canyons are formed after the formation of the Tertiary rocks. Secondly, valleys are mostly found transverse to the shore line, whereas on most shores structural features and faulting is mostly parallel to it. Thirdly, dendritic pattern of tributary valleys is also not possible in the fault valleys.

The idea of sub-aerial erosion of canyon is possible by two methods only. Either the land was uplifted above the sea level on which the valleys were carved which subsequently subsided, or the sea level was

¹ Gregory, *Geographical Journal*, Vol. 77, 1931., p. 127.

were for a short period during which the canyons were sub-aerially eroded and later submerged when sea regained its normal level. Further, the canyons are bordered by smooth slopes of continental shelf, which represent no structural disturbance. Again, the sub-aerial valleys do not seem to be connected with canyon at many places and even the heads of the canyons are seen at variable depth in the same area.

Considering the facts which show the possibility of diastrophic origin, it does not seem altogether impossible that canyons are deepened by it. Fosse de Cap Breton is also found related to an orogenic zone. Similar tectonic changes are founding Esmeraldas canyon amounting from 13 or 20 fathoms to 200 fathoms. In Japan, Sagaru Bay was subsided in 1923 and increased 100 feet in depth. Submarine canyon in Tsuruga Bay was also deepened. Hence there is a tendency to think that after the formation of the canyon by some other agency, the deepening was done by tectonic changes of the land.

Sub-aerial erosion. The shape of the submarine canyons, their apparent relation to existing river cut valleys and their situation along the valley mouths have led many investigators, especially Shepard (1941), to suggest that submarine canyons were cut down by rivers at some time when the land surface was above the sea level which later on subsided in recent geological time. Many explanations afforded by Shepard exhibit sub-aerial erosion of the submarine canyons. As early as 1863, J. D. Dana attributed the sub-aerial origin to the trenches found before Hudson mouth. The valleys in Java Sea are marked as drowned valleys, sub-aerially eroded, as the distribution of bottom sediment and under sea continuation of the alluvial tin ores of Singkep prove.¹ Again, thick sequences of tertiary non-volcanic elastic sediment on most of the islands indicate that in the past the land must have occupied the area which is at present deep sea. A fresh evidence is supplied by the submarine slope of atolls and barrier reefs, which extends thus to a depth of about 500-600 m. This slope can neither be formed by talus nor by loose material. Philippine canyons, according to Shepard, show a concave upward curve, typical of the stream valleys. Submarine topography around volcanic island Bogoslof in Bering Sea shows concave slopes on the sides just similar to East Indies. One of the valleys is 60 miles long and at a depth of 7800 feet below sea level. The pattern of the canyon is dendritic. In front of Salinas river, the Monterey canyon also shows deposition of the sediment and consequent changes in the level of the land. Monterey Bay is a depressed part of the land adjacent to mountains.

As an explanation of the formation of these canyons Shepard maintains that they were eroded at the time of emergence of land, then obliterated by deposition of sediment after subsidence and appeared again by down sliding of sedimentary filling and water sapping. Thus Shepard stressed the importance of recently submerged gorges as the cause of the submarine canyons. Hull also regarded the sub-aerial origin of these canyons. According to him the uplift was in the Tertiary period when continental platforms were created and valleys were formed. Following this, a

¹ 'Sub-aerial and Submarine Relief in East Indies', *Geographical Review*, Vol. 40, 1950, p. 486.

submergence has brought the present features. The idea is further strengthened by the winding nature, steep sides, and the tributary formation of the canyon. Adour canyon, whose bed is still deepening at its head and widening at tributary level, also confirms the fact.

Against the idea of submergence of land, W. M. Davis writes that two opposite suppositions may be made regarding the manner in which the submarine continental slope was temporarily upheaved. Firstly, the upheaval should involve a little more than an unbending of the slope itself on a huge line along the shore without any equivalent upheaval of the present land area.¹ The river deepens on this upheaved off shore belt, suggesting the slow and prolonged rise of the shore. ② Again, after this uniform upheaval, there must be a regional subsidence resulting in immense deepening of the present valleys. The refilling would then result in the present level of the submarine valleys. But no such geological evidence is afforded in favour of this movement, as greater vertical oscillation of land is needed to explain the origin. Nevertheless, such rising of the shelf, for thousands of feet, remaining there for a short period and then being subsided to normal level is not possible in their short geological time. ③ Moreover, if shores would have submerged, abnormal shelves could be seen. This, again, is not found as the shelves normally terminate at the depth of 65 fathoms. ④ Further, subsidence would have also caused submarine canyons deeply penetrated over the land, whereas the heads of canyons are found farther away from the river valleys of the land. ✓

To avoid the above criticism of oscillation of land areas Emery and Shepard suggested that during the ice age the amount of water removed from the oceans would be to the extent of 1000 m, though even this does not explain the depth of the canyons amounting between 5,000—10,000 feet below sea level. There is no geological proof of this amount of lowering. Due to this lowering, the shelves were exposed above the sea level for a short time and the valleys were carved by sub-aerial agents. Again, when sea regained its normal level, the valleys were drowned but demonstrated sub-aerial eroded features.

Those who put forth arguments against this idea suggest that the sea was lowered only a few hundred feet, that is far below the amount that would be necessary to account for the canyons—specially those having 5,000 feet depth remain unexplained. Further, the cutting of terraces on the shelves due to lowered level should also be seen.

✓ **Submarine mud flow and land slides.** In 1932 Shepard presented a slightly different idea that canyons are actually older than the shelf, i.e. they were covered on uplifted land in Paleozoic or pre-tertiary period prior to the formation of shelves. Hence the shelf denotes the area formed by erosion rather than by deposition. The canyons were originally filled with sediment but later on they were cleared by land

¹ Mr. H. W. Hoots gives a possible explanation saying that after erosional reduction of the area, mountains were formed in Tertiary times up to 2000—3000 feet. During Pleistocene time the high lands were eroded and weak Miocene bed was faulted down, over which various sub-aerially eroded valleys had formed. But according to this idea all coasts having tertiary mountains must demonstrate similar submergence which is not found.

There were two strong criticisms against this. Firstly, the shelf does not show deposition of sediment on it. Secondly, some canyons show that they were formed in Tertiary period. Later on Shepard combined both of his ideas. Before glacial period there were depressions on the continental shelf which were due to various causes (submerged valley, slides, or fracturing etc.). During glacial epoch when the sea level was lowered, the land valleys started flowing through the pre-existing depressions and hence formed the canyons in the newer sediment. Afterwards the sea retained its normal level and since then the canyons have steep slopes due to mud flows from time to time. The mud flow is not simply a slumping of oozy sediment, as cutting of the rocks and various newer outcrops are visible. This explanation of Shepard actually covers all the facts which are needed to explain a submarine canyon. But as land slide and mud flow are of greater importance in clearing the submerged ancient gorges hence its evidence is to be gathered.

Shepard and Emery (1941) state that mud flows are known to occur in the canyons, due to which they are kept clear of the unconsolidated debris. (It is not known whether they can erode rocks or not). Due to this process steep slopes are found in the canyons and fine sediment is also accumulated at the bottom. It is believed that the uplift of the continents during the Tertiary times caused acceleration of river action. The result was that the portion of the sea was filled by this excess of sediment brought through new valleys. With the submergence of this land, the valley was deepened below sea level. The deposition of clay and colloidal matter takes place in the canyons. When it is saturated and stirred by the action of waves, then it is subjected to land sliding. Thus the mouth of the valley is kept open, while the landward portion of the canyons is blotted out due to straightening and filling up.

For evidence, Shepard quotes the situation of most of the canyons off the mouth of the present rivers or old rivers. The submarine valleys do not penetrate the coasts as streams because that part of the shelf is not subject to land sliding, but here deposition takes place. Again, coarser sediments and lesser gradient also prove the action of some land sliding. Examples are also not lacking when cables have been found buried by land slide material, or left suspended due to sliding of the material underneath it. The evidence of breaking of cables, and being buried under debris for more than 100 miles in some cases is related to the submarine earthquake resulting in submarine landslides. Shepard and Gregory provided various examples in favour of it. But the breaking of cables does not prove land sliding in canyons as the displacement of the ocean floor would create steep cliffs or faults that would naturally help sliding. Moreover, greater sediment on cables proves that sedimentation has been going on for a long time and it is not necessarily due to land sliding.

Other proofs afforded by Shepard in this connection are the discovery of Corsan Gorge near the Grand Bank just after the earthquake of 18th November, 1929. These ideas were also criticised on the basis of the location of the above gorge being 340 miles farther from the place where cables broke and the possibility of mistakes during the oceanic survey before the occurrence of the earthquake which did not reveal any depression on the shelf.

Further, if landslides do occur, the mouth of the canyon should reveal it in the form of accumulations. Though they are stated to occur in front of Corsan Gorge and Columbia River, yet they need a careful investigation to supply solid proof. U 2 5

There is another difficulty if we believe that the sub-aerially eroded valleys were previously filled by sediment and later on revealed by landslides in recent times as found in the canyon of the Grand Bank. The deposition process is usually slow, and all the debris during melting of glacial ice would not easily fill the valleys. Then, again, during the deposition period earthquakes would be active but their effect on clearing the valley should be considered nil, whereas in the present time an earthquake can create landslides in submarine valleys even located 500 miles away from its epicentre. K 2

Shepard's observations in Sagani Bay during Japanese earthquake of 1923 show the changes in the depth of the canyon. This may be due to earthquakes no doubt, but it in no case proves land sliding. Similarly, just along the Californian coast, changes in the depth of the canyons were noticed. Shepard attributed them to the erosion by shallow water currents. Thus there is no need to attribute the deepening or origin of the canyons to the landslides. 52858

Apart from it, other objections to the theory are many. There is no proof in support of the regular phenomenon of land slides. According to Johnson,¹ "It rests upon a rather complicated series of improved assumption that great quantities of loose sediments have been deposited in older canyons cut more compact material composing the shelves on either side; that the sediment will be fluid enough to slide or flow at the slight disturbance of distance earthquakes of moderate intensity, yet compact enough to build up a fill sometime thousands of feet in thickness." Thus the fact that land slide could occur downwards up to thousands of feet, without any feature of accumulation at the mouth of the canyon, is not explained by the theory.

There is a possibility of landslides forming scars on the continental shelves, but the origin of the submarine canyons is not possible by them. Stetson and Smith also agree that short 'landslide' valleys can form due to lowered sea level, but general origin of canyons is not possible due to it.

Thus landslide and mud flow alone are not capable of creating the submarine canyons, though they can accompany other phenomenas as well as help in deepening of the canyons. "In the origin of the submarine canyons at least 10,000 feet above sea level is demanded, and that would violently disrupt the geological and biological theories." Davidson points out that the average depth of canyons about 200 to 300 fathoms is 3 or 6 times deeper than the glacial lowering of sea level and below the reach of erosional agents. Hence W. M. Davis states that "The method of submarine canyon formation, by sub-aerial agents due to uplift of land or submergence of sea seems impossible or non-operative." Submarine valleys should be regarded as merely an element in the geological history of its coastal region. The land on the coast should be marked,

¹ *Journal of Geomorphology*, 1939, p. 126,

r sea, is uncertain in action and the bottom is covered by thick sediment."¹) Thus submarine canyons could not result from the building up of the shelf as it would need thousands of feet depositions of sediment and the formation of the features over the side of the canyon.

The above two suppositions are not possible. Moreover, some shelves show hard and smooth surfaces (north-east coast of North America) and in absence of strong current to erode the shelf. Normally greater depth of the canyon needs large currents to erode them. Stetson (1935) criticised the idea on the basis of high degree of lithification of rocks on submarine canyon walls and steeper slopes for any unconsolidated material to be there indicate that they are not easily to erode. (Daly suggests that the lithification of the shelf sediment is not resistant to the running water. It is actually not hard.) After contact with the atmosphere the rocks are known to have become soft.

Submarine Density Currents. This idea involves the movement of submarine currents due to certain factors which erode the submarine valleys and restrict the deposition of the sediment. It was Adolf von Salis (1884) who first suggested that the submarine currents are created at the bottom due to temperature differences. Horrmann while studying hydrographic survey of the lake Constance discovered them in 1883 so that heavy cold water sinks on the floor as bottom current which erodes the sub-lacustrine trench at the mouth of the Rhine river. Later on, Florel (1885) suggested density difference to account for the possible submarine currents. According to him the trenches of the Rhine in lake Constance, and that of Rhone in lake Geneva are due to "non-deposition along the axis of the current (being cold the river water subsides below lake water) while deposition active in the stagnant water on either side, builds up lateral dykes."¹ In his previous presentation of the idea the erosion of the trenches was considered to be the main phenomenon. But later on, he rejected the idea of erosion or there being original depression in favour of non-deposition in the axis of the trench and greater levee building phenomenon along the density current due to sudden mixture of fresh water along the margins. He argued that erosion in front of river mouths may be possible to erode the upper part of the trench whereas farther from the river mouths or 200 m. deep, the erosion gives way to deposition.

Florel The origin of the density current was due to density differences created by river waters at the surface of the lake. The lower temperature (during summer and spring river water remained colder than the lake water, hence it subsides as being heavy) and excess of sediment of river water (this is the turbidity current) accompanied by salinity factor (Rhone water has greater salt content than that of Lake Geneva) created sinking of highly dense surface waters to the greater depths of the lake bottom. In 1887, Florel had also tried to explain various submarine canyons found in front of great rivers such as Congo canyon etc. on the basis of turbidity and temperature-salinity currents. But his idea was rejected, by Angelo Heilprin an advocate of the existence of submarine canyons unassociated with river mouths; even the association of low gradient canyon with the big rivers of the continent; and thirdly, due to an absence of levee like features on the shelf.

¹ Davis, W.M., 'Submarine Mock Valleys', *Geographical Review*, Vol. 24, 1934, p. 297.

Buchanan states that density differences arise due to salinity contrasts created by fresh river water so that a surface seaward current of light water moves above the landward dense water current. In 1936, Daly also advanced this theory of density currents, produced by the suspension of much fine grained sediment which flows down the slope and erodes the canyons, particularly during the intervals of lowered sea level during the glacial periods.

A few arguments are also given against the density current theory. In general the difficulty arises when at one place low gradient density current only prevents deposition of sediments in the channel of the open ocean, whereas it builds the nearby areas on either side of the stream by deposition in the enclosed seas. Again, density currents are mostly found in reservoirs, but there is no evidence of their existence in the sea where the density stratification of the water impedes the vertical flow.¹

Ground Water Sapping and Spring Sapping. Various canyons do not lie before the river mouths. Hence Bryan has suggested that the notches cut back in the face of the continental scarp may have grown by headward erosion through the agency of normal ground water sapping when the region was above sea level,² e.g. the side notches of Colorado canyons prove the fact. The development of such channels provides a dendritic form (or tributary development) specially on lines of weakness such as soft rocks, joints and faults. Though sapping is a natural phenomenon of geological structure, yet it is doubtful to believe that sapping could excavate the notches thousands of feet deep and many miles backward, only if there is a valley carved before. They normally occur on weak areas. Further, groundwater sapping above the sea level also does not seem possible.

Later on, it was suggested that submarine canyons are produced here as "subterranean rivers" had their outlets below the sea level, Roche-Poncie explained Fosse de Cap Breton and Milne (1897) discussed submarine springs on the shelf representing underground flow. Benest in 1889, Smith in 1902, and Commander Gorceix in 1922 also suggested that submarine valleys are formed due to the action of underground streams producing caves and sink-holes under the oceans. Some rivers terminate in lagoon and are diverted to subterranean course in order to appear as spring in submarine gullies. But the above phenomenon may be cited as local. A slightly different idea is presented that ordinary groundwater percolating through permeable rocks and carrying out on the ocean floor along faults would also create linear depressions. It is criticised because dendritic pattern and faulted structure are not associated together and the latter is not found on all the coasts. According to Smith the springs along the Californian coasts are at least responsible for the absence of deposits in the valley heads, if not for the formation of the valley.

The existence of such subterranean rivers below sea level is proved. But their capacity to erode submarine canyon is not estimated.

Further, ideas are also put forth in the form of solution along the faults by down filtering marine water which absorbs the nearby clay etc.

¹ Sverdrup and others, *The Oceans*, 1942, p. 41.

² *Journal of Geomorphology*, Vol. I, 1938, p. 127.

results in the form of caves. In 1912, Dunhalen, explaining Fosse Cap Breton, stressed the importance of its narrow and deep form and warm water in the bottom of the trench which indicates the occurrence of thermal springs in fault line. There would not be deposition along the spring and greater deposition on the sides along it. But due to non-universal application on all the coasts and the doubts regarding capacity of rising underground waters to form currents strong enough to prevent deposition in the trench, the statement is rejected.

According to Douglas Johnson (1939) the origin of the submarine canyon is related to the solution and erosion resulting from the outflow of underground water in the form of artesian springs. This force has been acting for about 60 million years when the former coastal plain of America was up to Appalachian mountains. Artesian aquifers have been known to occur in sedimentary beds which should have sufficient hydraulic pressure to overcome the pressure due to sea water on the submarine continental slope. Thus it causes a copious and vigorous outflow of artesian waters that may well have gushed from submarine outlets under very high pressure even at depths of 10,000 feet and more and would erode the material of the sheet.¹ The position of these springs would determine the depth of the canyon and their backward migration on the shelf would locate the canyon.

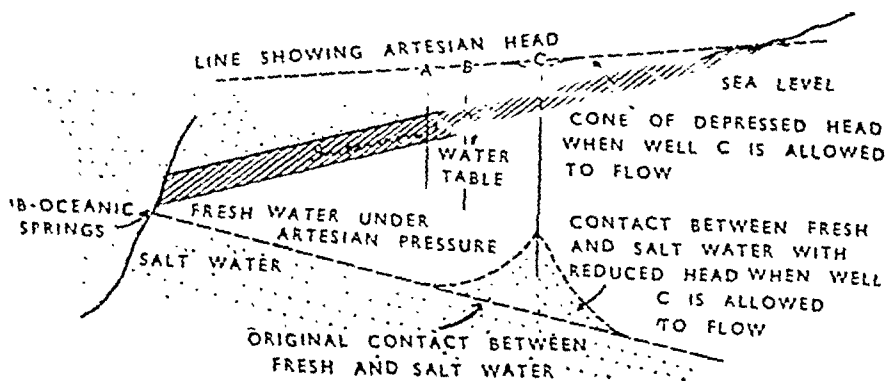


Fig. 19. Diagram showing possible conditions of contamination of wells by seawater. Vertical scale greatly exaggerated. (After Stringfield, Florida Geological Survey). Also shows artesian water appearing as sub-oceanic springs on the seaward face of the continental shelf.

(From *The Journal of Geomorphology*, Vol. II, March 1939).

Johnson remarks that if there is no basalt and hard rock, a canyon 2 miles long and 300 feet deep may develop due to solution along the shelf only during Pleistocene time. Valleys in San Miguel Gulf show that along much of the distance the edge of the shelf is a steep cliff more than 6000 feet below sea level, thus offering favourable situation for spring sapping and solutions as interpreted by Johnson, otherwise the formation

¹ *Geographical Review*, Vol. 30, 1940, p. 250.

of cliff and lowering of sea level would have presented difficulties regarding the gorge which should be found in front of Darien debouchure.

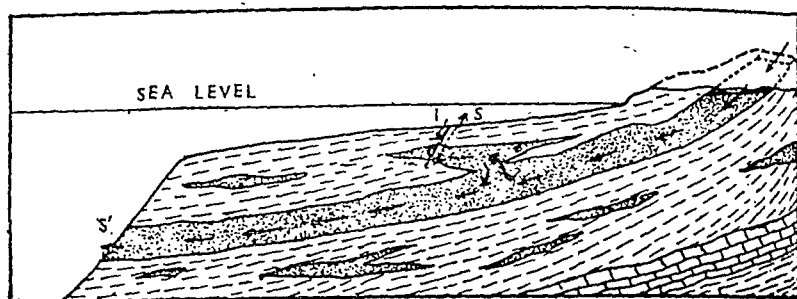


Fig. 20. Artesian conditions permitting leakage out of (dotted arrows) or into an aquifer according as the head is high (H) or low (h). Vertical scale greatly exaggerated.

(From *The Journal of Geomorphology*, March 1939).

The validity of the submarine springs is proved by the occurrence of fresh water spring upwellings on small islands just off the coasts. Similar springs and fresh water occurrence in depressions are also found on the shelf which prove their outlet under sea. Keilback has observed numerous springs with copious outflow off the Dalmatian Karst region as low as 700 m. Milne and Benest assert that cable breaks along the shelf are due to undermining by ground water springs and hence sliding of mud along the slope. The reports of the springs prove their existence farther from the coast also (as far as 125 miles) depending on the outcrop of the sloping impervious bed. On the shelf this will be determined by the geological conditions of the rocks. The temperature (recorded to be about 80° F) and the great pressure under which the artesian water emerges from the shelf gives them a good solvent action. Hence various carbonates, chlorides, sulphates, silica, iron etc. are mixed in the water which increase the specific gravity of the spring. Brown has pointed that sometimes the artesian springs, coming out on the shelf, lose their force due to lowering of the head, hence sea water enters in it and flows out from the lower spring at the outcrop of impervious bed on shelf. They can be found in shallow as well as deep water. The artesian spring would usually result on the shelf even at 10,000 feet depth below sea level if the pressure at the outcrop is greater than the back pressure caused by ocean water. During Pleistocene period, the land was slightly higher and the glacial level lowered and artesian springs reached a greater depth with greater force than is now.

It may be argued¹ that the deposition of fine silt at the front of the shelf would most likely seal up the outcrop, or the water being pervious formation may thin out and disappear before the seaward force of the shelf is attained. As regards the first, proofs are lacking to show extensive deltaic development at low angles in the open sea where currents are active. Hence shelves are mostly non-deltaic and usually expose

¹ *Journal of Geomorphology*, Vol. 2, 1939, p. 153.

the original structure. However, if deposits do exist on the shelf they form loose sliding deposits which are easily removed from the artesian spring mouths. Thus the question of sealing does not arise, and the springs usually occur on the seaward face of the shelves at the bedding outcrop or across the beds on the upper surface of the shelf.

It is also found that greater quantity of sea water moves out due to consolidation of the rocks on the shelf. This process is a regular one and has been helping in the artesian springs outflow. As regards the capacity of these springs to erode, various examples of surface spring at valley head are noted in Florida (2 to 8 miles backward erosion with 100 feet deep valley). The nature of the erosion or spring sapping would be to form a backward migrating valley, steep heads and cirque like appearance on land surface. Bryan believes that submarine canyons can form by spring sapping in favourable geological conditions. The spring sapping has been active since past geological times. (It is also proved by mud slides on the shelves). The main action of the springs would be to dissolve the rocks of any composition (with a variable time factor) and thus produce the canyon. The material eroded and deposited in the past would also be dissolved. The pressure of the underground water at 10,000 feet depth and the solvent minerals in sea waters would help a rapid solution. (Joly estimates that sea water is from two to fourteen times more effective in dissolving rocks than the fresh water). Davis also believes in the role of sea in solution of rock. Thus if the spring sapping solution is added by the mechanical erosion or disintegration of sediment the formation of the canyon after a long geological time would become possible. But many canyons would develop and those canyons would be able to cut back deep into the shelf which are formed geologically. The possibility of canyons being filled up by sediment is not found because the seaward slope of the shelf would naturally drag the most mud outward. Spring sapping in general forms the canyon just similar to land valley pattern. The sides of the valley are usually steep and the bottom is uneven due to occasional slumping of mud and gravel.

According to the above hypothesis canyons should develop on all the coasts, but specially in areas providing good structural basis for artesian springs. In areas where current etc. are active as depositional agents, the canyons are rare.

Some arguments are put forth against this theory. In the first place, it is very rare that soluble material is found along the shore, and the strike of the rock is found parallel to the submarine canyons. Secondly, the depths of the valleys, especially of Burica-submarine canyon, prove that a greater period of formation is necessary. Thirdly, solution would have been relatively more effective if the springs were hot. Fourthly, the canyons of old massifs are not possible under this theory. Lastly, the spring action would probably form a depression rather than a canyon.

Turbidity Currents. The idea of turbidity currents was first recognised when fine silt was found to be lying at the bottom of the canyon. It was agreed that the phenomenon could not be due to erosion (by salinity or temperature currents) but due to deposition by the currents bringing ample fine sediment from the land. Such currents

are known as turbidity currents because they hold sediment in suspension which keep their density higher and help in flowing along the shelf. They originate due to heavy on-shore winds, which create pilling action along coasts and a seaward turbidity current below the surface. The difficulty arises in assuming the long-time transport of sediment in the sea without being deposited (chemically the sediment settles in salt water with rapidity). The fine clay and silt could remain in suspension in a stagnant river's water for days and months.

W. M. Davis (1933) was perhaps the first to suggest the occurrence of turbidity currents accompanying glacial changes in the sea level as the possible cause of these valleys which are named by him as 'Mock Valleys'.

Many years before Davis put forth his theory, [W. E. Rither]¹ examined Vincente submarine valley, 15 miles south of San Monica coast (southern California) and said that inshore material is carried in this valley and there are natural channels through which currents flow. Tangier Smith said that the majority of Californian valleys were formed or kept open by some currents in operation. P. D. Trask referred that Huenewe submarine canyon has fine sediment at the bottom and no agency preventing it is found.

But after minor observations, outflowing bottom currents during great storms are found here which sweep away fine sediment and prevent deposition in the canyon whereas during fine weather the sediment is redeposited, just similar to the deposition of sediment in the river valley after the subsidization of the flood. These submarine currents are observed off Vincente, Huenewe, and Mugu (off San Monica coast) etc. There is a long shore south-east current along the Californian coast (known by the dissection of the beach drift). It is inferred that a back set eddy current is frictionally driven by it and located near the coast. This eddy current interferes with the main current but once mock valleys begin to start they are not restricted. Other valleys of this coast also exhibit outflowing sea floor current deflected from the dominant surface current. Whenever they are accelerated by storms, they are capable of drifting large quantities of inshore detritus towards the sea.²

The north-east coast of Australia gives an example of strong deep submarine degradation by an equatorward sand drift, to which Agassiz has attributed the absence of the coral reef. Similar currents are found in South Australia. Hedley accounted the alternating depths of the sea floor to such currents.

[Lawson] has also considered the idea of submarine currents maintaining a passage way along the coast. The bottom of Congo and Fosse de Cap Breton shows silt and clay deposits in the valley bottom because the less vigorous current flows through it. In those valleys where gravel and debris are found currents of extraordinary power are needed to

¹ Rither, W. E., 'A Submarine dredging on the coast of Southern California', *Science*, Vol. 15, N. C., 1902, p. 55.

² *Geographical Review*, Vol. 24, 1934, p. 297.

be such material and to transport it through the canyon. The deposition of fine sand at the bottom does not go against the existence of current in the bottom because when storm prevails on the coast, sand, clay and mud is swept away into the valley and consequently it is weakened deposition starts. The same was found by Fosse de Cap Breton canyon, which he thought would have been obliterated had there not been some current in operation which runs the canyon.

W. M. Davis showed that seaward moving hydraulic currents can carry material in the Monterey Bay. There is an onshore storm. The water can gain load or hence increase in specific gravity. Thus valley formation would be added by the seaward bottom current. Davis said that due to coastal upheaval of mountains the excess sediment is deposited on shelf, which obliterates the old canyon route. Due to an outgoing bottom current in the bay and an inward surface current to compensate the former, the path is cleared. According to Davis, this explanation fits in for the upper course of the valley, i.e. 23 miles where the valley is narrow, steep sided, and well defined and shown by 5 to 50 fathoms. The nearby area is comparatively shallow which slopes gently from the shore onward to 30 fathoms during the glacial period, the level was lowered and with the help of a storm, to which valley head reacts that is narrower and deeper in storms and shallower in fine weather, the accelerated degradation can be conceived.

Daly elaborates the above idea slightly in a different way. During a lowered glacial level or due to onshore storms, the shelf sediment is eroded by the wave attacks. River water may also provide less sediment. Hence sea water changes in the sediment mainly in suspension, increases in density and naturally slides along the shelf as turbidity current. The process is helped by the piling of the water by wind driven onshore hydraulic current. Hence the carving of the canyon becomes possible. The horizontal extent of the erosion by turbidity current depended on the rate of the sediment deposition. But during glacial lowered level, canyons could be eroded just near the slope. Gradually the process would help to increase the canyon erosion. The difference between the ideas of Davis and Daly lies in the fact that the former stresses the action of wind generated hydraulic current over the turbidity current in the formation of the canyon, whereas the latter gives importance to the turbidity currents which are helped in their action by the onshore wind current.

Buchanan also thought similarly. The flow of the fresh water over oceans beyond the river mouth causes deep counter currents that might excavate submarine canyons. He explains this in reaction to the Congo canyon which according to him was formed due to the prevention of river mud being deposited in its long axis. Thus the canyon sides are formed. On the shelf onward current exists and to compensate it an inward current is found at the bottom. Wherever these currents do not act, mud is deposited. However, two difficulties appear in relation to this canyon. "The main ocean current near the Congo mouth runs to the north so it is conceivable that the northern wall of the canyon may

have been built in this way, but it is not easy to see how the southern wall is accounted for on this view. Further, as the top of the canyon seems to coincide with the upper level of the continental platform on the west coast of Africa, we do not seem to have here an adequate cause for the formation of the canyon with built up wall which on reaching a certain height extends many hundreds of miles in either direction along the coast of Africa."¹

Kuenen is also in favour of turbidity hypothesis. Further proofs of the validity of turbidity currents in submarine canyons are given by him. Landslides (Kuenen states that these currents are capable of canyon formation) on continental slope can transform into turbidity current by addition of water. The velocity becomes greater and the erosion is facilitated. Once the canyon forms, further land sliding is increased due to steep walls. Smith and Stetson agree that turbidity current would result in distribution of sediment on the shelf. The sub-surface outward flowing density current of Gibraltar has comparatively greater velocity and capacity to erode than the surface current flowing inwards from Atlantic.

Various criticisms have been put forth as regards Daly's turbidity hypothesis. Firstly many old investigators have stressed the importance of temperature differences in creating the currents, viz. Zeppelin (he concluded temperature and turbidity factor) and Heim. Heim has pointed out that in some cases the turbid water of the river is lighter than the lake water. Thus the former spreads over the surface and does not create the currents. Similarly, river deep water would create lesser salinity of the sea water, hence the lighter water would float which affects the bottom. Nile and Ganges muddy water floats seaward for 100 miles while Amazon water moves for 200 miles. Thus it seems improbable that turbidity currents must arise by settling of sediment from a muddy layer which is overlying. Thus the muddy layer would be higher than the fresh sea water just below. Further, along the shelf where wave action is noted the temperature is also slightly higher than the lower depths. Thus the turbid water becomes still less dense. Secondly, others were also doubtful about the capacity of river water to erode only within that winter period when cold water sinks below the lake surface, according to some the trench was a tectonic depression. Thirdly, canyons often cut in hard compact rocks as along Provence and California which present further difficulty in the possibility of turbidity current erosion, as Shepard concludes about the rocky structure of Californian canyons. Thus greater strength of turbidity current is to be attributed to erode the valleys.

Bucher (1940) has pointed out that most of the currents in the canyon may be relatively of low velocity and would be therefore incapable of active erosion of rock. Hence he suggested rapid currents associated with earthquake waves set up in the sea by violent seismic motion of the sea bottom.² The waves are universal in application and could originate under sea by sudden displacement of waters due to breaks in rocks along the coast. They can also result from earthquakes or from volcanic eruptions. The magnitude of the waves is greater. They are very long in comparison to the depth of the oceans (e.g. 5 feet long

¹ Steers, J. A., *Unstable Earth*, p.55.

² Sverdrup, H. U. and others, *The Oceans*, p. 42.

ves in one inch water). Their capacity to erode the shelf increases shallow waters due to their horizontal back motion. Hence depressions are carved in the shelf and the sediment is easily carried away.

Dana has put forth a new idea of outflowing tide from New York Bay and from the adjoining bay, which is a main force along a frontal line in the shallow Atlantic border region and thus has an important effect on the bottom.

In short, we can say that bottom current of any intensity can be found at a depth, and can modify the sea floor profile either by erosion or by prevention of deposition. These can be supplemented by crustal deformation, volcanic eruptions, deposition of elastic material from the land, earthquake waves and storms. Recently Kuenen (1952) has put forth the idea that there are two types of canyons: those off the coast of Corsica and Provence representing stable areas, which are formed in hardness due to submergence of sub-aerial valleys; and those off the coast of New England, which are carved in the unconsolidated material and represent the action of landslides and turbidity current.

Apart from many observations and theories which give varied explanation of the origin of submarine canyons there is one point on which all agree and that is that the canyons are a recent geological feature, formed well within the most recent division of geologic time, the Cenozoic, and most of them probably have formed within the Pleistocene period. Bourcart maintains that the outcrops of rock along the canyon walls show almost recent sediment. French canyons cut lower Quarternary sediment, and Cap Breton trench cut Eocene rocks of the shelf. Similarly, New England and Californian canyons cut Pliocene and tertiary beds respectively. There are proofs that they are still in the process of formation. They are found in the regions of earthquake exhibiting weak area still mobile. Davis points out that the steep sides of the valleys show recent origin, because in areas of deposition and delta formation no such deep valleys can be found. Moreover, if they were old valleys then they could have been obliterated by the lowering of the sea level. On the contrary, their deepening still in parts shows how young they are.

Chapter 5 | BOTTOM RELIEF OF THE OCEANS

The study of the bottom relief of different oceans presents an important aspect of oceanography, as the relief controls the nature, character, and the motion of sea water.

ATLANTIC OCEAN

✓ Atlantic Ocean¹ is the most widely studied ocean and even minute details of it are recorded by investigators. The ocean, extending between North America and South America on the one hand and Europe and Africa on the other, communicates with the Arctic Ocean by small openings in the form of Norwegian Sea, Denmark Strait and Davis Bay. It occupies 82 million square km. which is one-sixth of the total area of the world or one-half of the extent of the Pacific Ocean. The shape of the ocean is rather irregular in the form of the letter 'S' indicating that the continents on either sides were once a part of the single land mass. It is wider towards the south (3700 miles, east to west at 35°S latitude) where it opens into the Antarctica Ocean and narrows down (Liberian coast is only 1600 miles away from Cape Sao Roque) towards equator between South America and Africa. After this it again widens in the north (3000 miles at 40° N latitude) and finally closes down due to the presence of Greenland in the form of narrow bays and straits. ✓ Out of the total area of the Atlantic, 24% area is less than 3000 feet in depth due to the shallowness of many enclosed and marginal seas and the width of the continental shelf. ✓ The bottom features of the Atlantic reveal four salient features as shown in Fig. 21.

✓
1. Continental Shelf. The region of the sea adjoining the continental land and having a depth of less than 200m may be regarded as the continental shelf. It is seen in conspicuous form all round the coasts of Americas and Africa, but it varies in width. At places it extends to 50 miles (up to 150 fathoms) while at others, it extends only for one or two miles. The width of the shelf varies according to the nature of the coast. Wherever mountain mass approaches the shores, the shelf is narrower as off the coasts of Africa from the Bay of Biscay to the Cape of Good Hope, and off the coast of Brazil between 5° and 10°S latitudes. The width is between 50-100 miles. However, along

¹ Good depth charts are available for the Atlantic Ocean, e.g. a general chart based on the records of the *Meteor* has been made on 1:20 million on the Lambert equal area azimuthal projection with isobaths at 500m. intervals (Stocks and Wust, 1935). Further, a basic chart of oceanic soundings on a scale of 1:5 million in 13 sheets (4 sheets published, Stocks, 1937) is also available.

Date Date

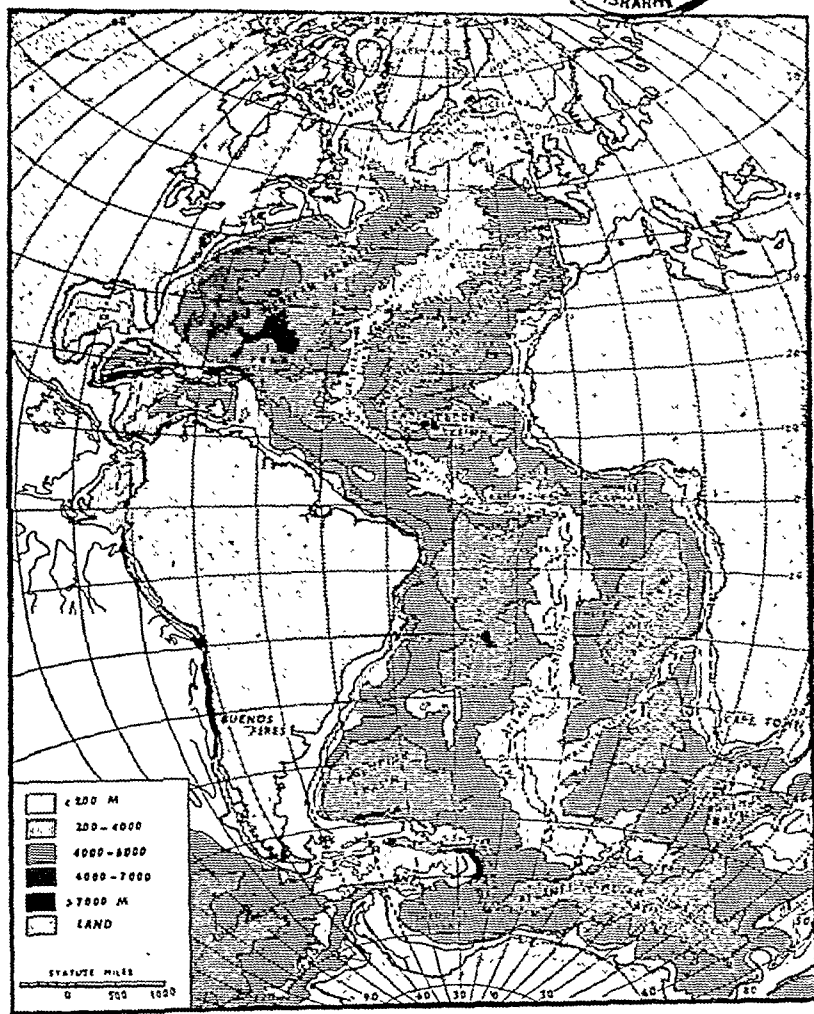


Fig. 21. Bottom Relief of Atlantic Ocean.

other coasts wide shelf is found ranging in between 150 and 250 miles as off the coasts of north-east N. America and north-west Europe. Even between Florida and Newfoundland, it is wider than the average as compared to the shelf on other side at northern shore of the Bay of Biscay and along Labrador. North of Cape Hatteras the shelf is as much as 150 miles wide. Again, around Newfoundland and British islands, world's most wide continental shelves like Grand Bank and Doggar Banks are found. Around Greenland and Iceland also a wide shelf is seen. In the South Atlantic the shelf widens south of Bahia

Blanca along the S. American coast, and extends eastward and then southward towards the Antarctica continent where Graham peninsula is extended in the north and meets it. This broad continental shelf is again 100 fathoms deep and is known as Patagonian shelf on which are situated the islands of Falkland and S. Shetland.

Apart from the extension of the shelf in the ocean, most of the marginal seas are also situated on it. They are almost absent from the South Atlantic. The shallow Hudson Bay, the Baltic Sea, the North Sea (all 100 fathoms deep), the Davis Strait (maximum depth is 112 fathoms), the Denmark Strait, are all on the continental shelf. The two deep inland seas, the Caribbean and the Gulf of Mexico (maximum 2080 fathoms deep) in the west and the Mediterranean in the east contain depressions of over 1000 fathoms. At the Gibraltar Strait the depth is 200 fathoms, whereas in some areas it is 2000 fathoms and the deepest (2533 fathoms) is found between Crete and Greece. Further, the Atlantic Oceanic continental shelf has numerous islands, e.g. British Isles, Newfoundland, the West Indies islands' arc, the islands on the central ridge (as Azores, Ascension, Tristan da Cunha), the Wyville Ridge islands (as Iceland, Faeroes), the Volcanic islands (as Madeira, off Moroccan coast), the Coral islands (as Bermuda) and the complicated ridge islands as St. Helena, Trinidad, Falkland, South Orkneys, Shetlands, Georgia, Sandwich, and the plateau islands as Canaries, and Cape Verde islands.

2. Atlantic Ridge. The most striking feature of the Atlantic Ocean is the presence of a longitudinal rise, traversing the ocean from Iceland in north through equator to the Bouvet island in the south. The ridge was first discovered a century ago by a German oceanographic vessel 'Meteor', which crossed and re-crossed the Atlantic during the 1920's, and established the contours of the ridge. Later 'Atlantis' of Woods Hole Oceanographic Institution studied it in detail, specially in the vicinity of the Azores island.

The ridge rises near Iceland, from where through the median of a narrow Reykjanes ridge it turns south, south-west. In between Iceland and Scotland, this ridge is known as the Wyville Thompson ridge and forms the boundary between the Atlantic and the Arctic Oceans. The depth over this ridge is only 550 fathoms. South of the continental shelf of Greenland and Iceland, the ridge widens near about 50° N with a depth of the water between 2000 and 4000 m., and is known as Telegraphic Plateau because it was here that the first cables were laid. The plateau is wider in the south and slopes down suddenly towards east to form a deep basin.

To the west of this plateau a ridge bifurcates near 50° N towards Newfoundland coast, bounded by the contours of 3000-4000 m. It is known as the Newfoundland rise. South of this rise the Central Atlantic ridge follows a south-west direction along the coast of Africa and America in the middle of the ocean up to 12° N. Here it is seldom broken and disrupted. South of 40° N this ridge is somewhat widened towards the coast of Africa. and here Azores rise bifurcates from the central ridge. Again, just at the equator the Sierra Leone rise bifurcates towards the north-east coast of Africa and Para rise moves to

orth-west coast of South America. It is here that the central ridge turns sharply eastward under the bulge of Africa and moves towards the south.

Its general course is parallel to the coast line of bordering continents and throws off many branching ridges towards the coast. At 0°S the Guinea ridge bounded by 4000 m. contour is thrown off in a north-east direction towards the Guinea coast. However, the most important ridges in the south are those which bifurcate near 40°S where the central ridge has the maximum breadth (600 miles). Walvis ridge 3000 m. deep is divided from 40°S towards north-east and merges into the African continental shelf. To the west, Rio Grande rise is comparatively deeper between 3000 and 4000 m. and moves north-west towards the coast of South America up to 30°S . At 30°S , there is a hill like clustering of contours, exhibiting the submarine plateau connected by a rise. After 40°S the central ridge moves towards south-east and forms Meteor Bank and Cape Swell near about 45°S . It proceeds towards the Cape of Good Hope, south of which it is known as the Atlantic-Arctic ridge.

The central Atlantic ridge having the shape of letter 'S' is 9000 miles long. It traverses the ocean from north to south, and seldom falls 4000 m. below the sea level. Following the curves of the coast line and swinging from east to west, but mostly remaining in the centre of the ocean, it divides the Atlantic into two broad deeper basins on either sides.

The greater part of the ridge is submerged and its central backbone rises some 5000 to 10,000 feet above the sea floor. The width of the Ridge also varies from north to south—it is wider north of Telegraphic Plateau and also between 34° - 45°N . Further south, it narrows down to a minimum at the equator where Romanche deep (7370 m) divides the ridge into two parts. The northern Atlantic ridge is known as Dolphin rise, whereas the southern ridge south of the equator widens again after 30°S and is named as Challenger rise.

The ridge, though under the sea level, has many peaks thrust out of the darkness of the deep water above the surface of the ocean. These peaks are actually the islands of the mid-Atlantic. The highest peak of the Ridge is Pico Island of Azores. It rises 27,000 feet above the ocean floor, with its upper part 7000 to 8000 feet above sea level. South of this island is Cape Verde island at 16°N . The sharpest peaks of the ridge are the cluster of islets known as Rocks of St. Paul near the equator. They are quarter square mile in area and their rocky slope drops off at such an angle that water, more than a half mile deep, lies only a few feet off shore. In the South Atlantic, volcanic island, Ascension and other islands, as Tristan da Cunha, St. Helena, Gough and Bouvet islands, are also found.

Origin of the Ridge. Various authors have put forth their views regarding the occurrence of the central ridge of the Atlantic. Haug, Washington and Pratje have attributed this rise to the compression which formed this young geanticline. Wegener and Windhausen considered it as the former floor of the rift when Americas were drifted westward. Gregory believed it to be the central part of that portion of

Atlantic which sank after being fractured. Taylor and Daly considered it as a crustal strip left behind. Molengraaff believed it as 'Cicatrix' where the sima was laid bare when continents moved in opposite direction. Kober maintained the idea of sunken axis of post-Palaeozoic fold system. Baker thought it to be an arching due to tangential thrust in the sima when under the weight of the ocean the floor was forced to occupy a lower and shorter arc. Stille put forth an idea of a rising epi-rogential structure, and van Bemmelen stated it as an uplifted part. Different from others, Staub connects the northern section of the ridge with the trans-Atlantic Alpine folding, but he does not explain the southern half of the ridge.

✓ However, the two different theories of compressive and tensional forces go against each other. ✓ The idea of compression does not seem possible due to evidences of tension around the basin. Further, Stille also points out that all folding in the trough should be along the margin and not in the centre. Thus, the youthfulness of the topography based on compression ideas stated by Gregory, Baker and Stille is opposed to the hypothesis based on tensional idea by Taylor, Daly, Molengraaff and Kober. Again, the movement of the continent towards the ridge is negated on the basis of the lack of young fold ranges on the western border of Africa.

✓ Hence the question arises whether such medial range can develop in a tension basin, as a consequence of sub-coastal adjustment. Du Toit states that when the stretching process proceeds, the floor of the ocean would be more or less even, but there would be warping up of the central part of the ocean in order to adjust to the ceasing of the tension. In this process depressions would naturally occur near the land where sedimentation would be greatest, and the oozes would only accumulate over the central zone. Hence bulging of arch is established here and the conditions would favour further disturbance and vulcanicity along its axis, thus accentuating the central structure and simultaneously loading and sinking on either side of the central zone. Such a structure would not be fixed but could move horizontally within certain limits. Thus it is also suggested that as each deep of Atlantic is drained by a big river discharging waste on the floor and, as Du Toit mentions that, since the last Andean phase was characterized more by uplift than compression, the evolution of the mid-Atlantic rise could have dated back to the Pliocene age.

✓ In support of the above views, the volcanoes are found from Iceland to Bouvet, where lateral rise joins the main axis and possibly stands on lines of fracture or shear. As Brouwer remarked, some differential horizontal movement is doubtless in progress. Such movements bring strips of crustal rocks near the sea level as in Ascension and St. Paul's rocks. Just at the equator where Romanche deep (7370 m), the region is highly seismic. Here the central ridge bends abruptly towards west, south-west.

✓ Further, it is also proved that the upper layer of the crust of the earth is also well developed beneath this ocean as Gutenberg indicated by the analysis of earthquake waves and the absence of gravity anomalies. Thus the gravity over the central ridge should be same throughout,

though occasional high anomaly can be attributed to deposition of heavy basic matters.

As a result of practical observations, the extraordinary pattern of Atlantic floor, i.e. the 'zigzag stem and its branches' that reach out in various directions to the continental frame, is highly suggestive of east-west stretching. Some of the submerged branches are strips not completely torn away from the adjacent land as the Walvis ridge.

Staub has suggested that the ridge is the terrestrially evolved Alpine structure forming many curved ranges, mostly convex to the south. In the associated basins, all dependent upon Newfoundland and Venezuela on the one side and Spain and Morocco on the other, there is manifestation of a sunken continental segment while Alex Du Toit maintains that rise and sink are stretched, distorted and broken wrinklins of the crust evolved under simultaneous drawing away of Americas from Euroafrica. Under such conditions east-west tension, north-south compression and upwelling of the sima in between oceanic basin is found.

✓3. **Basins.** The central Atlantic ridge divides the ocean into two broad basins, which are further divided into many sub-basins. Wust has suggested that 4000 m. contour be used as the boundary of basins.

✓(i) Labrador Basin. It is situated between the continental shelf of Greenland in the north and Newfoundland rise in the south in 40° - 50° N. The depth exceeds 4000 m.

✓(ii) Spanish Basin. In the eastern Atlantic along the Iberian peninsula there is a basin known as Iberian basin, situated north of Azores rise in between 30° - 50° N. The basin is deeper in its southern portion where its depth exceeds 5000 m.

✓(iii) North American Basin. It is perhaps the biggest basin in the North Atlantic situated between 12° - 40° N from the coast of America up to 55° W. The depth of the whole of the basin is more than 5000 m with few deeps in the central part.

✓(iv) North and South Canary Basin. Separated by the Azores rise in the north, Canary basins are two circular areas, 5000 feet deep, but joined by a narrow passage of depression.

✓(v) Cape Verde Basin. Extending longitudinally with a curved area in the north, Cape Verde basin is situated between central ridge and Africa between 10° - $23\frac{1}{2}^{\circ}$ N. The basin is also 5000 m. deep.

✓(vi) Guinea Basin. Along the Guinea coast of Africa stretching from north-west to south-east, the basin lies between Sierra Leone and Guinea ridge. It is in the form of separated basins along the coast between 4000-5000 m. depth.

✓(vii) Brazilian Basin. In the South Atlantic the Brazilian basin extends south of Para rise at equator up to 30° S.

✓(viii) Angola Basin. Along the African coast from north-east to south-west Angola basin extends up to Walvis ridge. It is also 5000 m. deep.

(ix) Cape Basin. It is situated west of Africa between 25° - 45° S.

(x) Argentina Basin. A circular basin extends from the coast of Argentina up to south Atlantic ridge between 35° - 50° S. The average depth is again 5000 m., but its southern part reaches the depth of 6000 m.

(xi) Agulhas Basin. South of the Cape of Good Hope this basin is broader in 40° - 50° S after which by a narrow depression it is joined by another basin of the South Atlantic.

(xii) Atlantic Antarctica Basin. A continuous and irregular east-west depression extends north of Antarctica continent along 60° S.

4. **Deepes.** The lack of recent foldings along Atlantic has resulted in the absence of deeps. Moreover, the slope of the basins on both sides of the ridge is also not much and therefore deepes are lesser. According to Murray 19 deeps below 3000 fathoms can be located in the Atlantic. Important deeps are Nares Deep (6000 m) north of American Basin, Puerto Rico deep east of Puerto Rico island, and Romanche deep (9370 m.) at the equator dividing the central ridge. Other deeps are recorded in Table No. 5 on page 44. In the S. Atlantic east of South Sandwich island, a deep longitudinal semi-circular trench is found. The depth is estimated to be 4545 fathoms. The cross section across the Atlantic reveals the bottom topography and its features, as shown in Fig. 22.

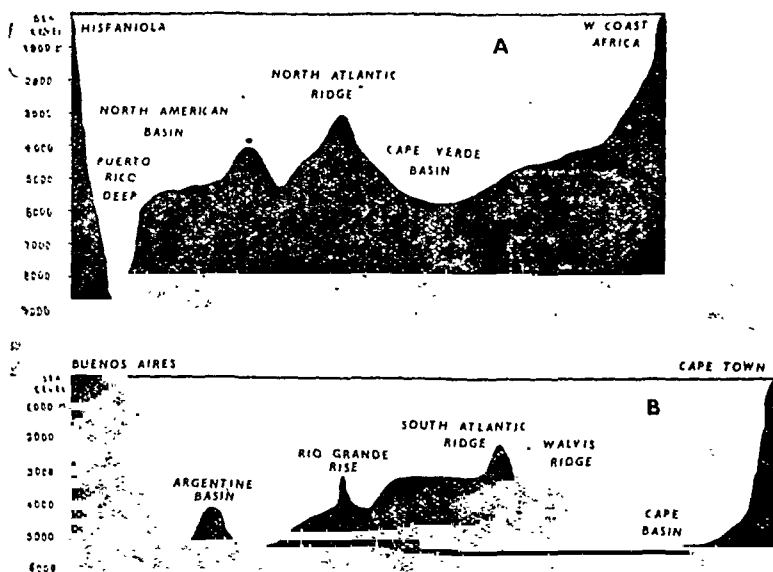


Fig. 22. (A) Cross section across the North Atlantic Ocean.
(B) Cross section across the South Atlantic Ocean.

SEAS ADJACENT TO THE ATLANTIC

Mediterranean. The Mediterranean¹, comprising the Black Sea, has deep elongated basins and depressions. The basin is sub-divided into series of north-south ridges parts of which extend above the sea level and separate many depressions and basins which are found extending from east to west. A ridge 4000 m. deep extending from the European coast near S. Italy to Africa is dividing the Mediterranean into western and eastern parts. The west Mediterranean is sub-divided into Algiers-Provençal basin and Tyrrhenian basin which are separated by 1000 m. deep ridge stretching from Italy to Tunisia, on which Corsica and Sardinia rise above the sea level. The eastern Mediterranean is again separated into two major depressions, the Ionian basin extending between Italy and Greece with maximum depth up to 4600 m. and the Levantine basin having depth between 2000-3000 m. The dividing ridges extend from Greece to Africa. The latter depression is in the form of isolated basin, having depths of 3000 m. in the west and 2000 m. along the coast of Syria. Apart from this, many depressions are also found south of Italy in the Adriatic Sea which affords an example of narrow and elongated depression between folded mountains, founded as a result of violent disturbances during the Tertiary times.

The continental shelf in the Mediterranean as shown in Fig. 23 is broad along eastern Spain, West Italy, west of Greece, north of Egypt and north-east of Tunisia and Libya, amounting to 1000 m. depth and between 50—150 miles width. The Adriatic Sea is wholly on the continental shelf which is 200 m. deep.

The Black Sea has a broader shelf of 200 m. in north along Russian coast, but an elliptical depression of 2000 m. depth is found in the southern part. At the connection between the Black Sea and the Mediterranean Sea, the depth at Bosphorus is only 400 m. and 70 m. in Dardanelles. At Gibraltar the depth is 320 m. with a 20 km. wide passage.

Caribbean Sea and Gulf of Mexico. This portion of the Atlantic is bordered by N. America and S. America. It comprises the Gulf of Mexico and the Caribbean Sea, which are separated by a ridge 1600 m. deep between Yucatan peninsula and Cuba island. Stocks (1938)² has charted the depths of the region and shown that the shelf between 200—1000 m. is south of Florida, north of Yucatan around Bahamas and Honduras, and along the east coast of Mexico. Generally, as shown in Fig. 24, the topography is rugged with trenches adjacent to steep-sided ridges along Cuba and Jamaica.

The basins found in this region are:

(i) Mexico Basin. It is a simple depression lacking irregularities, with a depth of 3000 m. The maximum depth of 4000 m. occurs in the western part. The area is 1·602 million km².

(ii) Caribbean Basin. The area is 1·948 million km². It is separated into sub-basins by Jamaica rise 1000 m. deep, e.g. west and east

¹ A modern bathymetric chart for the European Mediterranean has been given by Stocks (1938).

² A new bathymetric chart has been prepared by Stocks (1938).

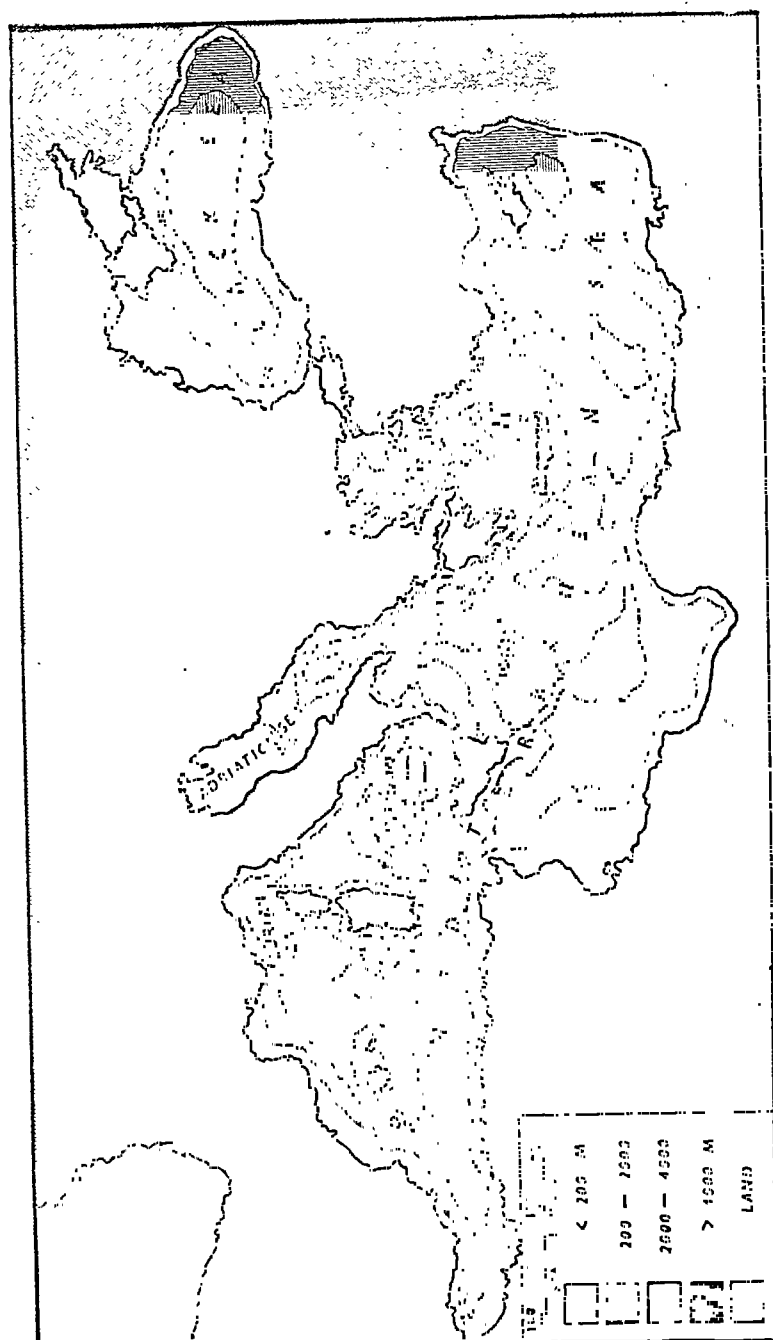


Fig. 23. Bottom Relief of Mediterranean Sea.

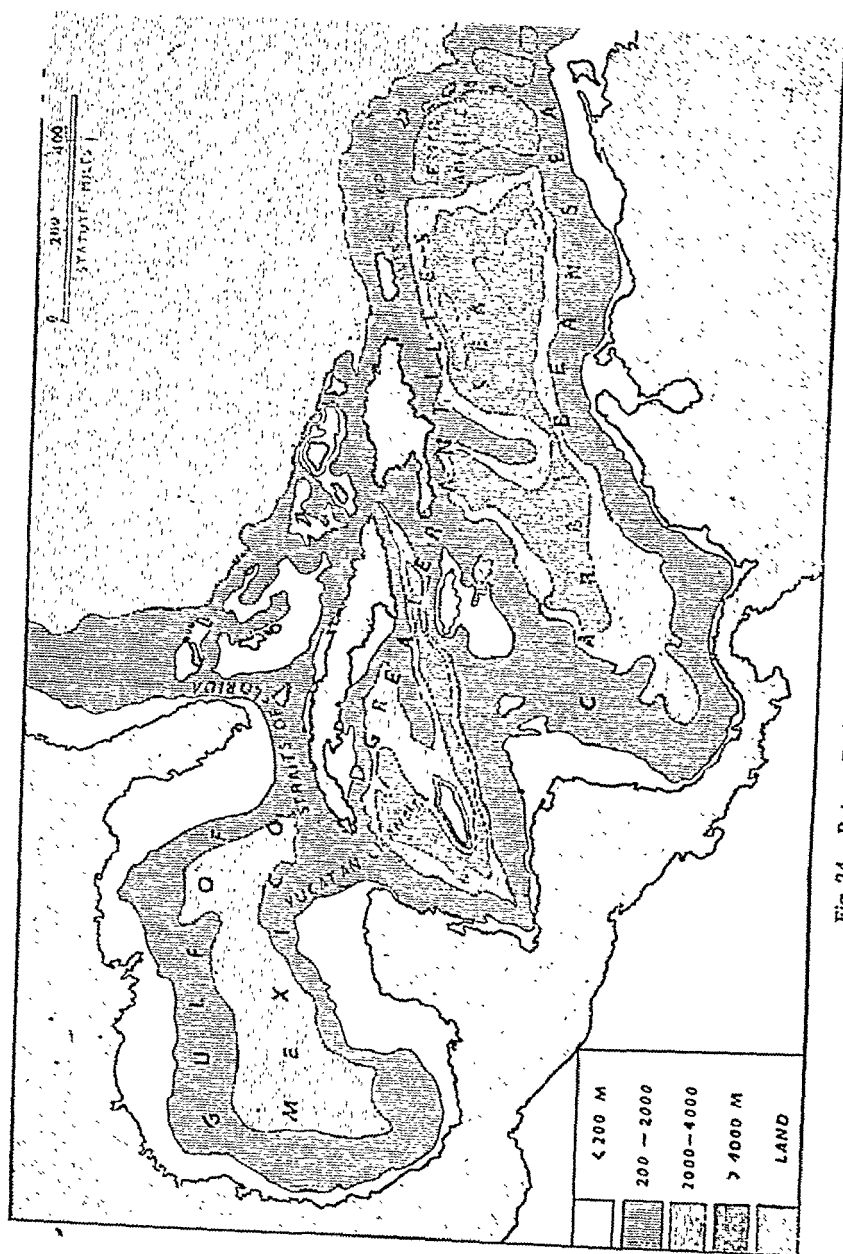


Fig. 24. Bottom Relief of the Caribbean Sea.

Caribbean basin, which are again divided into four basins : (a) Yucatan basin having 4000 m. depth and extends from Yucatan to Cuba; (b) Cayman trough separated from the Yucatan basin by a narrow sill (Cayman ridge) of 2000 m. depth is the deepest depression found in this area. Bartlett deep south of Cuba has 7200 m. depth ; (c) Columbia basin is in the eastern Caribbean and is separated by Beata ridge 2000 m. deep extending from Hispaniola towards south-west. It is 4000 m. deep; and (d) Venezuela basin is north of Venezuela, 4000 m. deep, with the deepest part of 5000 m. situated in the south. Aves Swell separates a small basin of 3000 m. depth in the eastern part of Venezuela basin on the northern side of Puerto Rico. And a longitudinal trench here measures greatest depth.

Other Seas. The Baltic and the North Sea are situated mostly on the continental shelf only 100 fathoms deep, and the passage between the Danish islands into the Baltic is only 11 fathoms deep. In the Baltic and North Sea, only in small depressions near about 320 m. depth is found.

In the other marginal seas on the American side, Baffin Bay has a basin only 2200 m. deep, whereas Hudson Bay is only 100 fathoms deep. Davis strait forms a shallow link 112 feet deep between the Atlantic and the Arctic oceans.

INDIAN OCEAN

The Indian Ocean¹ is a warm ocean blocked on the three sides by the continents of Africa, Asia and Australia. Most of the coast is made up of hard block mountains of gondwana remnant in Africa, Australia, Deccan plateau of India and Western Australia, but folded ranges are also found along East Indies. The shape of the ocean is said to be compact, with bold and regular coastlines. In the south it extends up to the Antarctica continent where it merges into the Atlantic and the Pacific. The average depth of the ocean is 4000 m., less varying and comparatively lesser than that of other oceans. Out of the total area, 60% forms the deep sea plain of a depth between 2000 and 3000 fathoms. As regards the marginal seas and islands, we find that due to surrounding plateau coasts, the marginal seas are few. They are Mozambique Channel, Andaman Sea, Red Sea and Persian Gulf. The islands in the Indian Ocean are of great variety, i.e. the large islands as Madagascar and Ceylon, the small ones as Socotra, Zanzibar and Comoro, the Andaman and Nicobar islands as a result of the submerged folded mountains of Burma, Laccadives and Maldives due to the submarine ridge and other small islands, rising from plateau, such as Kerguelen, and the volcanic cones such as Mauritius and Reunion islands.

According to Johnson in the Indian Ocean three distinct regions are traced out: (i) Area nearby Africa is less than 2000 fathoms deep carrying numerous islands, e.g. Seychelles and Madagascar. In isolated patches the water is less than 1000 fathoms deep; (ii) In the east there is the deeper part of the Indian Ocean with depths over 3000 fathoms. Here the continental shelf is narrower and steeper; (iii) The Central elevated part on which several groups of islands are found.

¹ Recent depth chart of the Indian and Pacific Oceans on equal area projection, on a scale of 1:60 million has been published by Schott (1935).

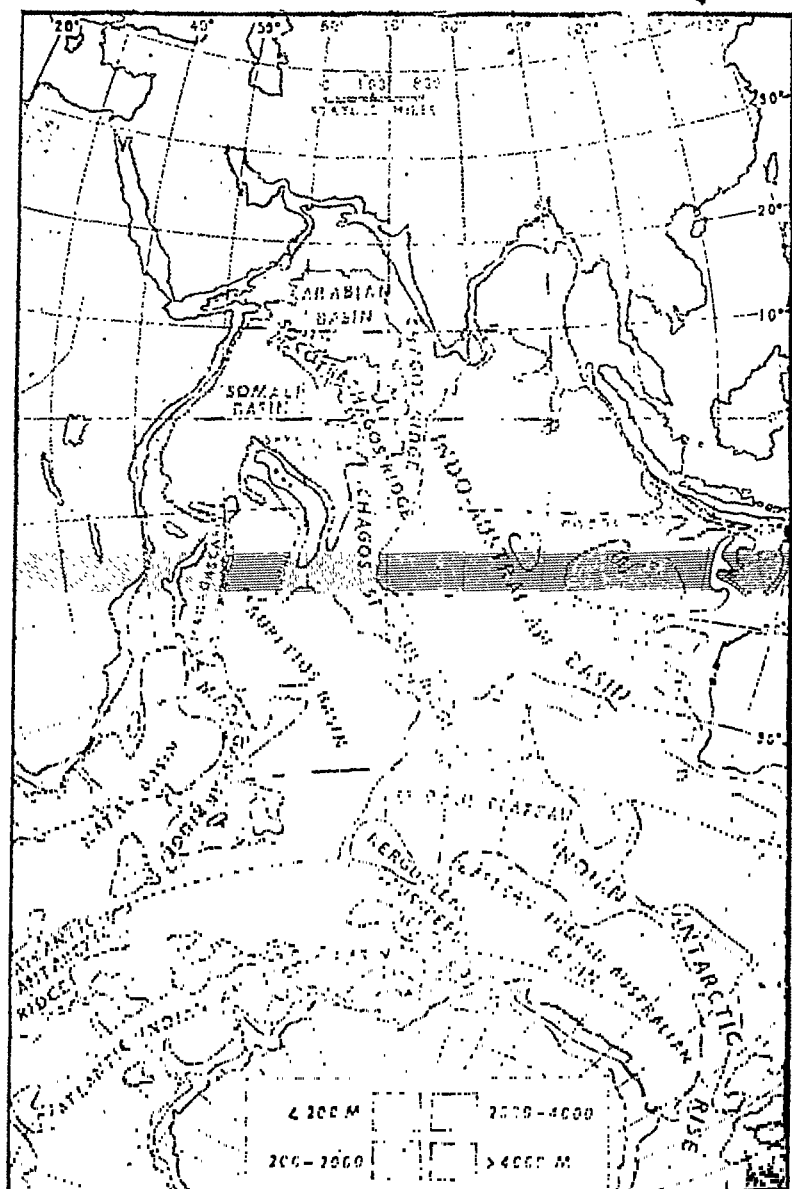


Fig. 25. Bottom Relief of Indian Ocean.

1. Continental Shelf. The shelf in the Indian Ocean is also of varying width. It is particularly marked by 600 feet contour along the shores. Wider shelf is found in the Bay of Bengal and the Arabian Sea. Here it attains its maximum width of about 400 miles. Along the African coast, the continental shelf is moderately wide but widens considerably near the Madagascar which itself stands on a deep shelf prolonged from the continent. On the eastern side of the Indian Ocean the shelf narrows down to 100 miles along Sumatra and Java coasts in the north and Australian coast in the south. In the extreme south, the shelf is narrower along the Antarctica continent.

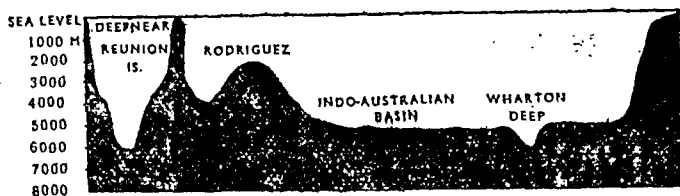


Fig. 26. Cross-Section across the Southern Indian Ocean.

2. Central Ridge. Like the Atlantic Ocean, the Indian Ocean is also traversed from north and south by the central ridge which is less than 12000 feet deep. It is situated in the middle, and divides the ocean into two basins on either side. It differs from the Atlantic ridge in that it is wider and does not extend so near the surface.

The ridge starts in the north in continuation of the continental shelf of the Indian sub-continent, on which Maldives and Laccadives are situated. Here the width of the ridge amounts to 200 miles, and is known as Laccadive-Chagos ridge. The bottom is about 6000 feet deep with an undulating crest bearing many small islands. This ridge henceforth is continued towards the south and between 0° and 30° S is known as Chagos Saint Paul ridge. South of 20° S, the direction of the ridge changes toward south-east and the width of the ridge is 200 miles. Further south, the Indian ridge widens 1000 miles in the form of Amsterdam-St. Paul plateau, extending between 30° – 50° S and 65° – 110° E. South of 30° S this plateau is divided into two separate ridges. On the west is 3000 feet deep Kerguelen-Gaussberg ridge stretching north-west to south-west between 48° and 60° S. In the eastern parts, the eastward continuation of semi-circular ridge is called the Indian-Antarctic ridge, which turns towards south at 140° E and merges in the Antarctic continental shelf.

This central ridge is bifurcated into many small ridges which reach the coasts of Africa and India. Near about 5° S Socotra-Chagos ridge is thrown off in north-west direction towards the eastern horn of Africa near Cape Guardafui. The depth here is also about 12000 feet. Just parallel to this ridge, 800 miles south, a curious curving Seychelles ridge is bifurcated near 18° S and runs parallel to the former, in the direction of African coast.

South of Madagascar, the shelf widens and moves towards south in the form of a ridge, known as south Madagascar ridge. It widens in the

south and extends between 55° - 45° E up to 48° S, commonly known as Prince Edward-Crozet ridge. In the Bay of Bengal another ridge Andaman-Nicobar ridge extends from the mouth of Irrawaddy up to Nicobar islands. The Carlsberg ridge has been found by recent surveys and it divides the Arabian Sea into two portions. It is narrow at its north-west end, but expands towards the Chagos ridge, with the water ranging between 2200 and 3000 m.¹

At some places, where the ridges are found above the sea level various islands peep out. On the central ridge are situated Laccadive, Maldivé, Chagos, New Amsterdam, St. Paul and Kerguelen islands. Seychelles and other groups of islands are situated on Seychelles ridge. In the south Prince Edward and Crozet islands are found over South Madagascar ridge. These islands show the existence of the highland submarine ridge in the Indian Ocean.

3. Basins. The central and other ridges divide the Indian Ocean into many basins having the depth varying between 12000-24000 feet.

(i) Oman basin. It is found near the Gulf of Oman on the widened shelf of Asia. The depth here exceeds 12000 feet.

(ii) Arabian basin. It is a circular depression situated between the African coast and Indian sub-continent. It extends up to 5° S in the form of a southward narrow extension of the basin along Socotra-Chagos ridge. The depth here is between 12000-18000 feet. Further, the Carlsberg rise divides the Arabian basin into two sub-basins—the eastern having depth less than 5000 m. and the western basin having more than 5000 m.

(iii) Somali basin. Surrounded by Socotra, Chagos and St. Paul ridges in the north and east and by Seychelles ridge in the south, the Somali basin extends up to the continental coast of Africa. It is more than 12000 feet deep and has a connection with the Mauritius basin found in the south.

(iv) Mauritius basin. It is a longitudinal broad basin extending from 10° — 50° S between Madagascar and St. Paul ridge. The basin has a uniform depth between 12000-18000 feet, but in few areas in the north it is deeper.

(v) Natal basin. West of the S. Madagascar ridge, the Natal basin extends south-west of Madagascar and south of African continent. Here the depth of the basin exceeds 18000 feet, and the deepest part is found west of Prince Edward islands.

(vi) Indian Antarctic basin. It is an extension of the Atlantic Arctic basin of the Atlantic Ocean, north of the Antarctic continent. The basin is more than 12000 feet deep and extends south of Prince Edward-Crozet ridge up to the Antarctica continent. The deepest part of 18000 feet depth is found along the parallel of 60° S.

(vii) Andaman basin. It is a comparatively shallow basin of 600-12000 feet depth, along east of the Andaman rise, in the Bay of Bengal.

¹ Du Toit, *Our Wandering Continents*, p. 227.

(viii) Cocos Keeling basin. It is perhaps the most extensive basin found on the eastern side of the ridge, extending from 10° N to 50° S. The average depth is between 12000—18000 feet, whereas the deepest part of 24000 feet is found south of Java Lesser Sunda Trench, and West of Australia between 12° — 30° S.

(ix) Eastern Indian Antarctica basin. This basin in south is surrounded by the curved form of the central ridge on all sides. It stretches south of 50° S and on the west it is bounded by Kerguelen ridge.

4. Deep. Out of the total area of Indian Ocean about 60% forms deep sea plain between the depth of 2000—3000 fathoms. The deeps are almost absent from this ocean except for Sunda trench (4076 fathoms) which is situated south of Java island along the folded mountains.

Marginal seas. The Persian Gulf and the Red Sea are situated on the continental shelves. The Red Sea is a clear-cut rift valley between Africa and Arabia. In the strait of Bab el-Mandeb it has only 200 fathoms deep water. The Persian Gulf is a shallow trough 50—200 fathoms deep. The Arabian Sea and Bay of Bengal are merely northward prolongations of the Indian Ocean. The Mozambique is a broad strait separating Africa and Madagascar and the Andaman Sea is a shallow enclosed sea.

ARCTIC OCEAN

Bounded on all sides by the continents of Asia, America and Europe, the Arctic Sea has a D-shaped plane with an average depth of 3500 m and with an area equal to $1/12$ of the Pacific Ocean. It has circular shape which communicates with the Atlantic through Denmark (800 m. deep) and Baffin Bay and with the Pacific through the Bering Sea (40—60 m. deep). The Arctic is mostly frozen with a 15 feet permanent thick ice due to which there are difficulties of sounding the bottom. In 1927 Sir Hubert Wilkins found the deepest sounding of 2975 fathoms, 550 miles north of Point Barrow. By 1940 only 150 soundings were made.

1. Continental Shelf. The shelf along the Arctic is wider in the eastern and northern part ranging between 100—400 miles. But in the west of North America and Greenland it is comparatively narrower. The depth here is less than 3000 feet. The widest shelves in the world are those bordering the Arctic, on which rise the large islands of the Canadian Archipelago, Greenland and most of the islands of Europe and Asia. The Barents Sea shelf is 750 miles wide. It is also relatively deep, the maximum depth not being more than 100 to 200 fathoms.

It is supposed that the floor of the Arctic is sagged and down-warped under the pressure of the glaciers. Nansen (1928) in his discussion of the topography of the Arctic said that U-shaped furrows scour the shelf of the ocean. One such trough is noted at the southern tip of Norway. These are attributed to the work of glaciers in the period when the sea surface was below the normal level.

2. Ridge. Till recently it was believed that the Atlantic ridge terminates at Iceland. But the U.S. Coast and Geodetic Survey has found that it continues further in the Norwegian Sea which is a part of the

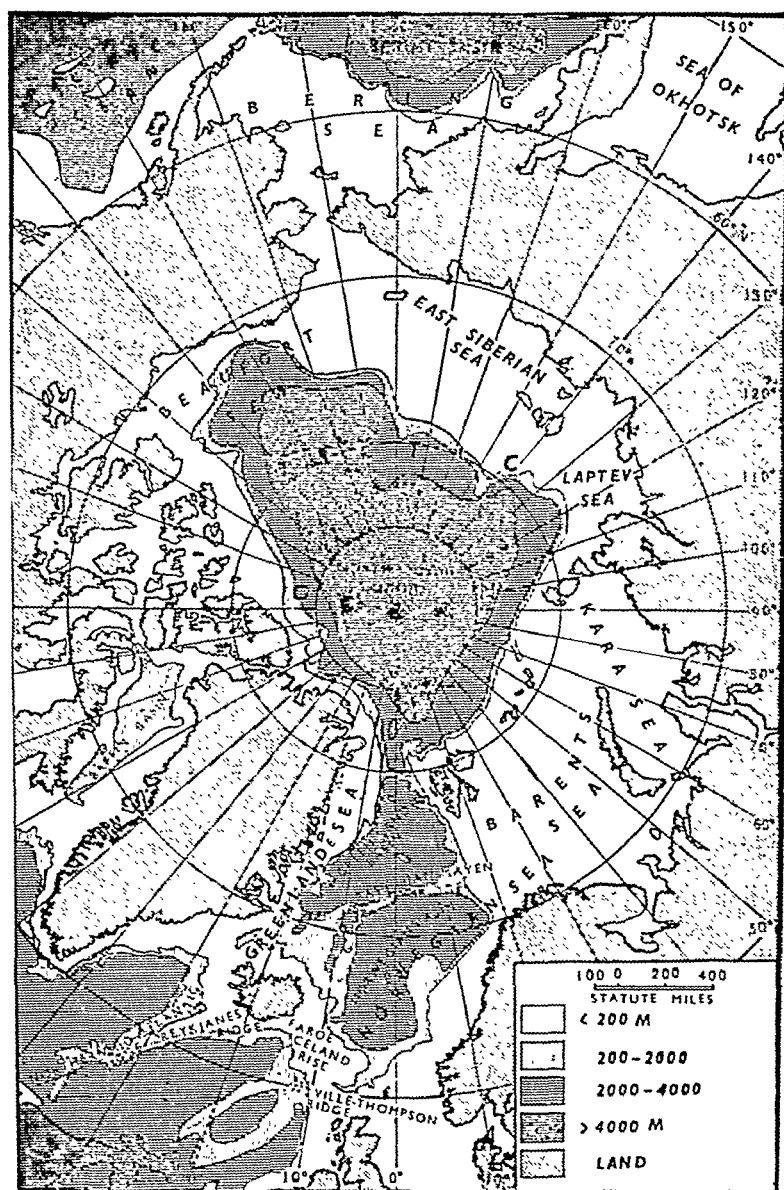


Fig. 27. Bottom Relief of Arctic Ocean.

Arctic Ocean. East of Iceland is Faeroe-Iceland rise extending from west to south-east along 10° W. This ridge further extends to the north up to 75° N in north-east direction and is known as East Jan Mayen ridge. It then turns abruptly towards the north and forms Spitsbergen ridge near 80° N. Water on this ridge is less than 3000 feet deep.

3. Basins. Several basins are also located in this ocean.

(i) Greenland Basin. The basin is between 6000—12000 feet deep and extends between Greenland and East Jan Mayen ridge.

(ii) Norwegian Basin. In the midst of the Norwegian Sea this basin extends from the central ridge to the coast of Norway. Water is 6000—12000 feet deep.

(iii) North Polar Basin. In spite of less number of investigations in the Arctic, the existence of Polar basin is not refuted. This basin extends in a circular form surrounding the North Pole, with an extended part towards the Beaufort Sea north of America. The average depth is between 12000—18000 feet. The maximum depth in this basin is found to be 3076 fathoms at 78° N— 175° W.

PACIFIC OCEAN

The Pacific Ocean, covering one-third of the area of the world, extends from the coast of Asia in the west to America in the east (10,000 miles) and from Bering strait in the north to the Cape Adare (Antarctica Continent) in the south (9300 miles). The average depth of the Pacific is about 15000 feet. Only 7% of its area is less than 3000 feet whereas major portion lies below 15000 feet. The descent from the coast to the plain is very much steeper. The oceanic surface is fairly uniform, with broad gentle swells and depressions.

It is the most unique ocean in many respects. It has a broad triangular shape. All along the coast for nearly 11,000 miles, the folded mountains are found parallel to it. In the north, it is completely blocked by the narrow Bering Sea from the Arctic Ocean. Pacific Ocean also records a variety of islands, amounting 20000 in total though their total area may be small. The islands are of following types: the larger continental islands (belonging structurally to the mainland, formed by submergence and separated by foundered basins) such as Aleutians, Islands off British Columbia, Chilean islands; the island arcs (a part of folded ranges with the volcanic peaks such as Kuriles, Japanese Archipelago, Philippines and Indonesian islands etc. and the smaller scattered islands. The latter are divided in two sub-types—firstly, the islands of Melanesia (Solomons, New Hebrides and Fizi), Micronesia (Marshall, Carolines, Gilbert and Ellice) and Polynesia (Society, Cook and Tuamotu islands) are included in Racial grouping; and secondly, the high volcanic islands (as in Hawaiian Mauna Kea island) and low coral islands (Fiji, Funafuti and Ellice etc.) are classed on the basis of formation.

In general we can say that the western part is mostly studded with islands but it is not the case with eastern Pacific where only Galapagos (600 miles west of Ecuador), Easter island (Volcanic islands on Albatross plateau) and Juan Fernandez (360 miles off Chile) are found.

urther, all along the coast, many marginal seas are found which are
stly situated on the continental shelf.

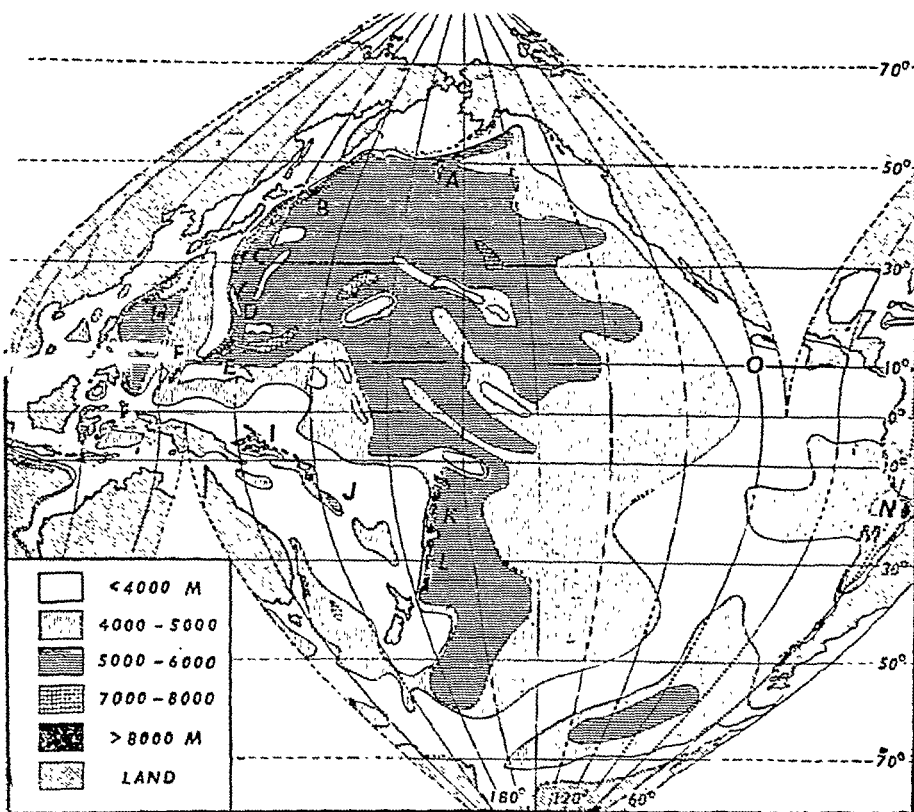


Fig. 28. Bottom Relief of Pacific Ocean (After Defant.)

According to Johnstone, the Pacific is divided into four parts:
(i) Northern Pacific. This is perhaps the deepest part of the ocean.
Most of the deeps are found bordering the island arcs. The average
depth of this part ranges between 5000—6000 m.; (ii) Central Pacific.
This part is studded with islands. Most of them are coral and volcanic,
including the Hawaiian swell. Recently H. H. Hess, of Princeton
University, found 160 flat-topped sea mounts between Hawaii and
Mariana and their summits are half mile below the surface. Various
sub-parallel island chains extend from New Guinea, New Caledonia in
south-west to Hawaii in north-east. Suess named these chains as 'Ocean-

ides' which constitute ripples on the ocean floor. Deepes are almost absent from this part and the average depth is near about 1000 fathoms. In front of the island arcs, the chains lie roughly parallel to the narrow 'back deeps' which range between 8000—10000 m. These deeps are aligned along a great circle extending north eastward from New Zealand to the coast of Vancouver. It is a rift valley as suggested by Gregory which divides the ocean floor, it forms the antithesis of the Mid-Atlantic Ridge. This part is 5000 m. deep. East of this high area, a depression is also found; (iii) South-west Pacific. This portion is again marked by variety of islands, marginal seas, continental shelf and submarine trenches. The average depth is 4000 m. which is less than the northern part; (iv) South-east Pacific. Broad submarine ridge and plateau are visible in this part, with a conspicuous absence of marginal seas.

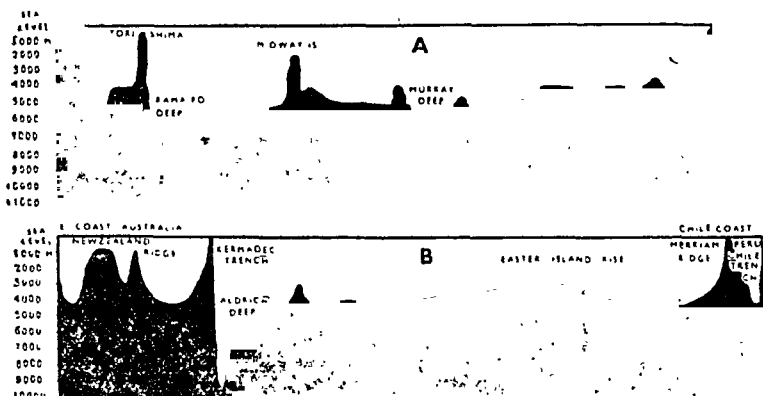


Fig. 29. (A) Cross section across the North Pacific Ocean.
(B) Cross section across the South Pacific Ocean.

Further, Alex Du Toit divides the Pacific Ocean in two parts: the eastern half consisting of few islands and the higher submarine plateau; and the western part consisting of deep area along the islands. Kober also attempts a new classification which divides the ocean in northern part, marking the chains of islands striking from north-west to south-east and the southern part free from chains of islands, but has coral and volcanic islands in abundance. Both areas according to him are supposed to be separated by a tectonic belt extending north-west south-east.

1. Continental shelf. Broad continental shelf is found along the eastern coast of Australia, East Indies, and the Asian shoreland. On this broad shelf are situated various islands of the Asian Archipelago, such as Kuriles, Japanese islands, Philippines, Indonesia and New Zealand. Many inland seas like the Bering Sea, the sea of Okhotsk, the sea of Japan, the Yellow Sea, the China Sea, the Java Sea, and the Coral Sea are also on the shelf. The average depth of the shelf ranges between 1000—2000 m. and the width varies between 100—1000 miles. On the western coast of the Americas, the continental shelf is narrower, only 50 miles broad. Thus the width of the shelf along the Pacific varies according to the nature of the coast.

2. Ridge. The Pacific Ocean is different from the other oceans in one respect that it has no central ridge. Only a few ridges can be located here and there, mostly on the eastern margin of the ocean, and the central swells are found in the middle of the Pacific. One of the most important ridges known as the East Pacific ridge or Albatross plateau (2200 fathoms deep) is quite extensive. From the coast of Central America towards south-west it is 1000 miles broad. It bifurcates into two, between 23° — 35° S. The eastern part is a broad plateau which joins the Chilean coast. The other ridge known as Eastern Island rise moves towards south. The depth of water on the ridge is between 2000—4000 m. The New Zealand ridge at 20° S in the west of New Caledonia is between 200—2000 m. deep. North of Fizi island the shelf or the ridge widens to form Fiji plateau (2000 m). West of the Great Barrier reef of Australia is the Queensland plateau (200—2000 m). The most important rise in the central Pacific is the Hawaiian swell, 600 miles wide and 1900 miles long, extending in north-west to south-east from 35° N to 17° N. The water here is only 1000 fathoms deep. On this ridge are situated the islands of Hawaii and Honolulu. Apart from these obvious but otherwise less distinct regions, there is also one area of 4000 m. depth, which extends from Japan continuously up to Antarctica except occasional breaks at 12° N, 10° S and 53° S.

3. Basins. Many depressions and basins, separated by numerous swells, are located along the Pacific Ocean.

(i) Philippine basin. East of the Philippine islands, this basin extends south of Japan up to 5° N. Its depth varies between 5000—6000 m. The western part of the basin is comparatively deeper than 6000 m.

(ii) Fiji basin. South of the Fiji island, separated by New Zealand ridge, Fiji basin extends between 22° — 32° S. The depth is more than 4000 m.

(iii) East Australian basin. A 4000 m. deep basin, compact and circular in form, extends east of Australia with deeper areas than 5000 m. found in the north. In the east the boundary is formed by the New Zealand ridge.

(iv) South Australian basin or Jeffrey's basin is a deep (5000 m.) longitudinal basin extending south of Australia.

(v) Peru-Chile basin. A wide and broad basin, 4000 m. deep is situated west of the Peruvian coast.

East of the Tonga Trench a deeper area (5000 m) is extended between 10° — 55° S and 150° — 152° W. Another extensive deep area (5000 m) extends north of Brooke deep in between Hawaiian island and the Asian American coast, which again turns to south near about 140° W and joins the deep near Ellice island.

4. Deep. Total 32 deeps are recorded in the Pacific, out of which most of them are in the trenches (longitudinal deep areas), parallel to the island arc or the mountain chain. These deeps are located mostly in the western part of the ocean. The following are some of the important deeps and trenches:-

(i) Aleutian trench. It is an arc-like depression bordering Aleutian islands; the average depth is about 6000 m. and the maximum recorded depth is 4199 fathoms.

(ii) Tuscarora deep and Japan trench. Lying parallel to the Japanese islands, the 8000 m. deep trench extends from 28° — 50° N for 1700 miles, and seldom more than 100 miles away from the land. In the south of the trench are situated Tuscarora deep (4655 fathoms) and Ramapo deep (5771 fathoms).

(iii) Swire deep. In the central part of the Philippine basin, this deep more than 6000 m. depth is situated.

(iv) Philippine trench. Extending 40 miles along the eastern coast of Philippine islands, this trench records the greatest depth (5902 fathoms) off the island of Mindanao, known as Emden deep.

(v) Nero deep. It is more than 9000 m. deep. Nero deep extends in the form of arch along Mariana islands. It is also known as Mariana trench, with recorded depth of 5395 fathoms in Mansyu deep.

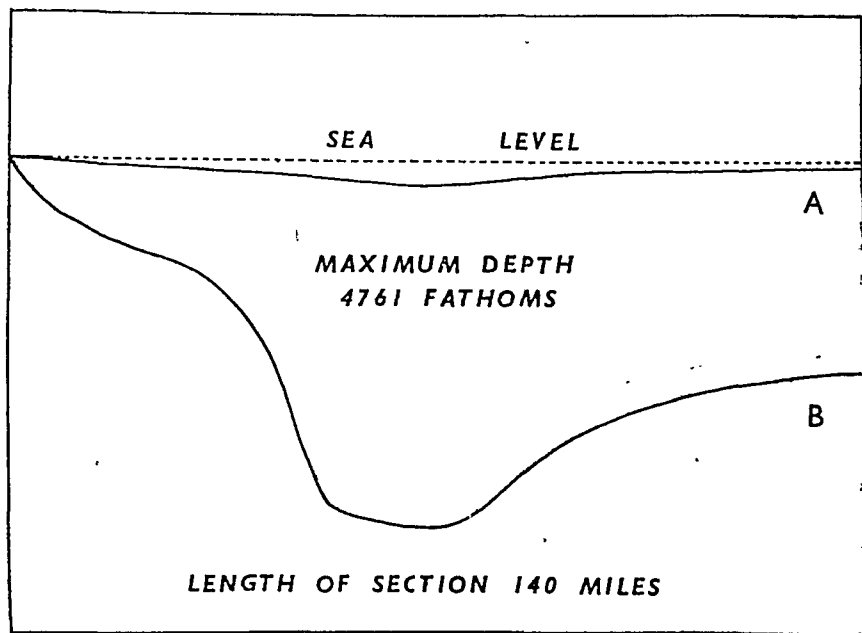


Fig. 30. Sections across the Tonga Deep.

(By permission, from *The Principles of Physical Geography*, by F. J. Monkhouse. Copyright. 1954. University of London Press, Ltd).

(vi) Tonga-Kermadec trench. It is a trough like depression, as shown in Fig. 30, extending from north-east to south-west along the Tonga and Kermadec islands. They are measured to be 8000 m. deep with Aldrich deep of 5155 fathoms.

(vii) Peru-Chile trench. It is situated along the Andean coast in the form of broken trenches. Atacama pit is the deepest area of 4175 fathoms.

(viii) Murray deep. In the northern part of the ocean along 30th parallel and 155° W meridian, it is situated.

Besides the above important deeps, the following are also worth mentioning : Ryukyu deep following the Ryukyu Archipelago, is 6000 m. deep ; Brooke deep (6000 m.) extending in north-east direction east of Nero deep; Bailey deep (6000 m.) an arch-like broad depression ; and Planet deep (7000 m.) east of New Guinea.

Marginal seas. Marginal seas in the Pacific are mostly in the western part of the ocean. As different from the Atlantic they are narrow and longitudinal in nature. On the eastern side only shallow Gulf of California and submerged-coastal seas near British Columbia are found. In the western part the important seas are—Bering Aleutian, Okhotsk, Sea of Japan, Yellow Sea, east and south China Sea and Celebes and Banda Sea (between Indonesian islands). Excepting the Yellow Sea, which is less than 100 fathoms, none of them are shallow. Most of their basins are deeper than 1500 fathoms. Celebes Sea records 2795 fathoms depth, or Sea of Japan, 1955 fathoms. Other seas around Australia, such as Gulf of Carpentaria, the Arafura sea or the Bass strait, all are shallow and lie on the continental shelf.

Chapter 6 OCEAN DEPOSITS

The study of oceanic deposits involves the consideration of the sources from which sediments are derived, the methods of transportation from the source to the destination, and the horizontal and vertical variations in their distribution. The unconsolidated layer of sediments, commonly known as 'Marine deposits', is the outcome of deposition of sediments due to continuous wearing of rocks along with the other materials such as plants, animals, etc. on the ocean floor. Various investigations of the deep sea bottom exhibit that it was by this method only that old sedimentary rocks consisting of organic and inorganic deposits were formed.

Herodotus was perhaps the first person who said something about the deep sea deposits. Ancient navigators along the Egyptian coasts were aware of the fact that the coarser deposits were laid along the continental margins in contrast to fine sediment deposits in the deep sea. Yet the ignorance about the deposits prevailed until 1773, when Captain Phipps for the first time presented a successful deep-sea sounding up to 683 fathoms and brought out blue mud from that depth. Various investigations of this type brought into light the nature and the type of deposits on the ocean floor.

However, the actual development of the study of marine deposits beyond hundred fathom line is attributed to Sir John Murray and his 'Challenger' expedition between 1872-76. The result of this intensive investigation was published in 1891, by the joint efforts of Sir John Murray and Professor Alphonse Renard. For the first time they put forth a world map of various oceanic deposits and had given a classification of deposits, i.e. Shore deposits, Globigerina, Radiolarian, Diatomaceous ooze, and Red and Grey clays. In spite of the continued progress in this branch of study we are still ignorant about the depth of these deposits, nature of the rocks that lie underneath and the rate at which the oceanic deposits are being accumulated.

SOURCE AND NATURE OF DEPOSITS

The marine sediments continuously being deposited on the ocean floor are derived from various sources and are distinguished by the nature of their source regions.

1. TERRIGENOUS MATERIAL

Under the process of disintegration and decomposition the terrigenous rocks, constituting mostly of hard rocks like igneous or

sedimentary, are shattered into pieces. The process of weathering, though not same everywhere, depends upon the character of the rock and climatic conditions. The amount of disintegration will depend upon the time for which the rocks are exposed. These rocks are disintegrated into smaller fragments entirely due to the aqueous denudation and are carried down to the sea by rivers as mud and sand.

The two types of weathering over the rocks result into two groups of terrigenous sediment. The first group consists of quartz, mica, feldspar, etc., which are the ultimate products of chemical weathering such as clay minerals, free hydroxides of iron, alumina, colloidal silica and materials in various stages of transformation.¹ The former results in the variety of sizes of fragments depending on the degree of disintegration, while the latter produces products of chemical weathering. The latter fragments of a terrigenous origin are laid down close to the shore, but the former are carried far away into the ocean. Hence a sorting action takes place in the process of deposition. Farther from the shore, big gravels would gradually change in the form of sand and mud if the arrangement is not disturbed by any fast current along the shore or by disturbance of the sea level.

On the basis of texture of the source region, mode of formation, nature of transporting agency and chemical composition, the sediments may broadly be divided into gravel, sand and mud. According to Revelle sand consists of more than 80 per cent of the material coarser than 62 microns in diameter; silty sand between 50 per cent and

TABLE I

Sediments	Diameter	
	Mm.	Microns
Boulder	...	256
Cobble	...	64
Pebble	...	4
Granule	...	2
Very coarse sand	...	1
Coarse sand	...	1/2
Medium sand	...	1/4
Fine sand	...	1/8
Very fine sand	...	1/16
Silt	{	1/32
		1/64
		1/128
		1/256
Clay	{	1/512
		1/1024
		1/2048
		1/4096
		1/8192

¹ Sverdrup and Others, *The Oceans*, p. 948.

80 per cent coarser than 62 microns ; sandy silt more than 50 per cent coarser than 5 microns and more than 20 per cent coarser than 62 microns ; silty mud more than 50 per cent coarser than 5 microns and less than 20 per cent coarser than 62 microns ; and clayey mud consists of material less than 50 per cent coarser than 5 microns.

A more detailed and broad classification of the sediments by Krumbein and Pettijohn is given in Table 1.¹

(i) **Gravel.** It is a coarse material ranging between boulders and granules (256,000—2000 microns)—that is from big fragments of rock eroded by waves and fallen at the coast line to the smaller fragments formed by the process of further disintegration and decomposition by transporting agencies. These gravels form mostly pebble banks along the coast and are too heavy to be transported. Its chemical composition is similar to that of sand.

(ii) **Sand.** A little finer sediment, ranging from very coarse (1000—2000 microns) to very fine (62—125 microns), sand is also the result of wearing of the land. Its size varies according to the nature and the capacity of the transporting agency. Thus sand may be carried into the sea by rivers in suspension and is deposited as soon as a mixture of sea water with fresh river water takes place. Further, sand may also be derived by the disintegration of the boulders and gravels deposited on the shore. Thus the sand deposits contain fragments of different rocks, i.e. igneous, or sedimentary or metamorphic, thoroughly mixed up. But the greater part of ordinary sand contains grains of quartz, for quartz is the most abundant constituent of the earth's crust, not subject to easy disintegration or chemical change. Such type of sand deposits are mostly found on all the oceanic margins and were first noted by W. H. Sidell in 1837 at the Mississippi delta. They are well sorted in a bay or beach and show marked variations in texture, as Martens (1939) noted along the eastern coast of U. S. A. and near river mouths shortly after floods. The decrease in the median diameter of the sand was noted by Shepard, McDonald and Revelle on the Pacific coast and also by Stetson (1938) on the Atlantic coast of U. S. A. Off Maryland and New Jersey well sorted sand is found.

(iii) **Silt clay or Muds.** These deposits in general are finer particles ($\frac{1}{32}$ to $\frac{1}{128}$ of a millimetre in diameter) much smaller than sand. Clays are somewhat finer than the muds and act as a binding material of sediments. Their proportion increases with the distance from the land. Clays and muds are different from sand as they do not only contain the quartz particles but they are also heterogeneous in composition and contain aluminium.

The origin of silt or clay is generally by the disintegration of the continental rock, both sedimentary and plutonic, which is carried by rivers into the sea, as suspended particles. In shallow bays, muddy waters are proof of fine clayey sediments ready to be deposited. When river water full of colloidal clay (that is, aluminous particles are in a state which is not that of mere suspension. They are too small to fall to the bottom as sediments. Consequently, they are not in a state of true solution—Johnstone) mixes with sea water, which has ionised sodium chloride in solution then the electrical changes occur and the colloidal

¹ *Ibid.*, p. 957.

clay takes the form of true suspension. Only then sedimentation takes place and water is found muddy.

It is, however, difficult to make a precise boundary between sand and mud deposits though mud line is easily detected around continents, somewhat outside 100 fathoms contour extending up to 1,000 fathoms. The deposition of the mud sediments is exceedingly slow and almost in complete stillness of the shallow waters or off the mouths of rivers where wave motion is very feeble.

Murray distinguishes between three classes of mud based on the colours of the sediments ranging from black to white with addition of blue, yellow, red or a mixture of all these.

(a) *Blue Mud*. It is the most common and widespread deposit in the deeper areas surrounding continental lands, and in partially enclosed seas. These fine muds mostly bluish-black are fine detritus resulting from the disintegration of the rock containing iron sulphide and organic matter. Their upper layer has a reddish tint due to the presence of ferric oxide or ferric hydrate. Blue mud is considered to be mainly formed of land detritus, hence carbonate of lime ranges up to 35 per cent. The process of formation of blue mud is helped by sulphur, which reduces the iron into a ferrous state containing 1 or 2 per cent of amorphous black organic substances. Most of the deposits of blue mud are found along the Atlantic, the Mediterranean, the Arctic and the Banda Sea. It occupies greater area among the various types of mud, e.g. out of 14½ million sq. miles of blue mud, the Arctic has 4 million, the Pacific 3 million, the Atlantic 2 million, and the Indian 1½ million square miles.

(b) *Red mud*. It is also a variety of mud differentiated from others by the presence of iron oxide and ochreous matter. The percentage of calcium carbonate ranges from 6 to 61, the average being 32. The siliceous organisms such as radiolaria and diatom are rare, while mineral particles of neighbouring land form 10—25 per cent of the red mud. As compared to blue mud, this variety is rare. Typical localities of its occurrence are Yellow Sea, the coasts of Brazil, and large areas of the floor of the Atlantic Ocean. Here the giant rivers bring down eroded material containing great amount of ferric oxide, which is prevented from being turned into blue colour as the reduction of ferrous sulphide and oxide is checked.

(c) *Green mud*. It is mostly seen off high coasts free from large rivers and their deposits, such as the Pacific and the Atlantic coasts of North America (South of Cape Hatteras and California specially), off the coasts of Japan, Australia and South Africa. Due to their position terrigenous particles are thus longer exposed to the dissolving action of sea water and are not soon overlain by sediments accumulating on their tops and gradually they are converted into green mud, containing green silicate of potassium and iron known as glauconite. As regards the minerals percentage, glauconite ranges up to 7-8% and has 0-56 % of carbonate of lime. Green mud is found between 100-900 fathoms depth. In deeper waters fine green sand composed of angular glauconite particles is found off the Cape of Good Hope where cold and warm currents meet.

In general the deposition of the terrigenous material varies from coast to coast. For example the deposits of Atlantic are more terrigenous than those of other oceans, as about half of the world is drained into the Atlantic Ocean which brings ample sediment.

The deposition of terrigenous material is mostly assorted, and hence Baulig thinks that it would result in the profile of equilibrium of the continental shelf. But great variations are observed, gravels are found far from the sea, whereas fine mud just along the coast, e.g. pebbles were found between 18 and 900 m. (off California), at 80 m. (off Lizard), at 105 and 110 m. (off Sicily). The distribution of sediment in English Channel is very irregular. Off Bay of Biscay a large mud bank is found. Shepard shows a strip of sand outside the mud zone. North-east of South American coast a vast mud bank borders for 2000 km. and extends in the deeper part also.

2. PRODUCTS OF VOLCANISM

There are two types of volcanic materials deposited on the floor: sub-aerial and submarine. The sub-aerial type consists of that material which is deposited on the land after being thrown out from a volcano and is subject to chemical or mechanical weathering. Later on it is transported to the sea by the action of rivers or running water. The lighter material thrown out may blow up with the wind, and would be carried far away into the sea. After floating for considerable time at the surface it is deposited in the bottom. Sub-aerial volcanic materials may also be derived not by eruption but due to the disintegration of basaltic oceanic rocks along the coasts. The process of weathering changes basaltic minerals, lava fragments, andesite etc. into fine sand or mud in the immediate vicinity on the shelf.

The volcanic particles are usually found greater in size along the shelves than in the deep seas, hence the former are often named as volcanic sand. The quality of the volcanic deposits resembles the blue mud. Their colour varies from brown-grey to black. They are found mixing with green mud and coral mud on the shelf wherever location permits and with oozes in the depth. Most of the volcanic mud is found around oceanic islands and covers an area of 750,000 square miles.

3. ORGANIC REMAINS

Apart from the material derived from land, sea deposits consist of calcareous or siliceous remains of organisms. These are particularly derived from the sea which is a source of life to various organisms. They are distinguished in two types: the Neritic and the Pelagic. The former consists of dead skeletons of marine animals and plants and the latter is a type of algae usually in the open oceanic environment. Under the action of the waves the organic shells and plants undergo mechanical disintegration and chemical transformation resulting in the formation of mud or sand, deposited at the bottom. These deposits contain only the carbonate of lime and thus they are different from other deposits on the ocean floor. The Neritic deposits are abundant in relatively shallow water of low salinity than in the oceans over great depth, due to the low temperatures of water at depth which is unsuit-

able for organisms and a small number of plants and animals present there to help in the formation.

On the shelf the deposits are mostly covered by the terrigenous material continuously being deposited on it. Hence it is only at some depths that we find these deposits. A difference is, however, noted in the nature of these deposits between continental shelf and the deeps. This difference depends on the nature of organisms whose dead skeletons form the material.

These deposits are found practically on all coasts. In West Indies Seas they have a maximum accumulation. The Bahamas are formed entirely of shells and blown up coral mud. The sand and mud of similar organisms is also found in the Caribbean Sea. In the deep seas these deposits surround the precipitous depth of the island along with the volcanic sands and muds.

The material which constitutes these organic deposits may be classified as follows:¹

(a) *Molluscan shells and their fragments.* (i) They consist of limy plates and spines of starfishes, sea-urchins, ophiurids and crinoids; (ii) calcareous tests or skeletons of alcyonaria, polyzoa, gorgonids; (iii) limy tubes of marine worms; (iv) calcareous tests of foraminifera; (v) limy spicules of sponges, alcyonaria and tunicates; (vi) calcareous exoskeletons or carapaces of crustacea; (vii) teeth, earbones etc of whales and sharks; and (viii) on a great scale, calcareous skeletons of reef building corals.

(b) *Siliceous animal remains.* They consist of: (i) Skeletons of radiolaria and (ii) spicules of sponges.

(c) *Calcareous plant remains.* They include (i) calcareous skeletons of algae—the coral lines and (ii) coccospheres and rhabdospheres with their disintegrated products.

(d) *Siliceous plant remains.* They have the skeletons of frustules of diatoms.

Oozes. Apart from the netritic deposits, the pelagic deposits are in the form of liquid mud, commonly known as ooze. When it is dried up it is transformed in a fine grained powdery mass, partly amorphous and mainly of little invisible shells. Formed by the above constituents, the oozes are classified as follows:

(i) Pteropod Ooze	}	Calcareous ²
(ii) Globigerina Ooze		
(iii) Radiolarian Ooze	}	Siliceous
(iv) Diatom Ooze		

¹ Johnstone, *An Introduction to Oceanography*, p. 74.

² As calcium carbonate is easily soluble in water, hence the first group calcareous oozes are found at lesser depth between 1000—2000 fathoms, whereas siliceous oozes are in greater depths as they are less soluble. The name of the oozes are after the most predominate type of organisms constituting them.

The calcareous materials are found in abundance in the ocean water in the form of floating organisms. Foraminifera are abundant and form Globigerina, whereas shells of planktonic molluscs are known as Pteropods. These organisms, mainly living in the shallow water, contribute mostly to this type of deposit especially in lower latitudes, and where terrigenous material is scarce.

The siliceous materials are not as important as the calcareous skeletal and are distinguished by the presence of silica which is actually derived by a group of protozoa (radiolarians) and benthic animals (notably sponges) which secrete the specules of silica. By virtue of being less soluble they are found at greater depths.

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(i) *Pteropod Ooze*. Most conspicuous floating molluscs named pteropod forms this ooze. The other shell that is found with it is heteropod, the proportion being 35 species of the latter and 32 of the former. It is a calcareous ooze containing 80% of calcium carbonate. The shells of this ooze are quite thin and mostly conical and easily soluble. The diameter is $\frac{1}{2}$ an inch. It is found in shallower waters (800-1000 fathoms), far from the continents on tropical ridges and in warm waters specially in coral reef regions. With the increase in depth it gives way to red clay, and is very rarely deeper than at 2000 fathoms. Hence its dead shells are absent from the deeper deposits. This ooze predominates in the western and eastern Pacific, small patches near Azores, Antilles, Canary island, central submarine ridge in the Mediterranean Sea and the Indian Ocean.

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(ii) *Globigerina Ooze*. This deposit as a rule is a dirty white coherent powder when dried up. Two-thirds of its weight is due to calcium carbonate present in the form of detritus. After washing up of finer material a coarse granular residue is left and this is called ooze. It is made up of shells of various foraminifera, but especially those of the germs from which this deposit gets its name *Globigerina*. It also contains calcareous remains of coccoliths, molluscs, worms and echinoderms etc. But only those are called by this name which contain 30% of carbonate of lime. The colour as commonly seen is milky white far from the land, but near the coast blue, grey colours predominate. It also varies from white yellowish to greyish, depending on the source material.

The average composition of this ooze as noted by Challenger is 64.47% calcium (whose proportion varies from 30% in 2575 fathoms to 97% in 425 fathoms), 1.64% siliceous content (mainly radiolaria), 3.33% minerals and 30.56% fine washings. Among minerals, glauconite is widely distributed though not abundant and occurs in nodules; phosphate is rare and localized, varying greatly in size and form; manganese is not abundant. Apart from the above minerals, quartz, volcanic glass, magnetite and mica etc. are also found.

This ooze is perhaps the most widespread in warm and temperate waters of the Atlantic, along the eastern and western continental shelves

in the Indian Ocean and in eastern Pacific Ocean (absent from N. Pacific). In north it extends up to Norway and Greenland. It covers a total area of $49\frac{1}{2}$ million square miles, that is 29.2% of the ocean floor. Among all the oceans, $22\frac{1}{2}$ million sq. miles of area in the Pacific, $12\frac{1}{4}$ million sq. miles in the Indian, and $14\frac{3}{4}$ million sq. miles in the Atlantic is covered by Globigerina ooze. Vertically this ooze is found beyond 2000 fathoms but mainly extending from 3000-4000 fathoms. Wherever it is not covered by terrigenous deposits it is also found in shallow seas.

(iii) *Radiolarian Ooze*. This ooze is dirty grey powder which becomes a clay like substance when dried. It is also formed by the shells of the organism foraminifera. The shells are formed of siliceous matter rather than of calcium. The siliceous remains of radiolaria shells are mostly abundant in it with some amount of clay content. Radiolarian ooze is also considered as a variety of red clay very much resembling it but varying only due to the presence of radiolaria. The amount of calcium carbonate is insignificant and it varies from 5 to 20%, the average being 4%. With the increasing depth, calcium carbonate disappears.

It is a characteristic of deep water and is abundant in the tropical regions of the Pacific. To a smaller extent it is also found in the Indian Ocean and in patches along globigerina ooze in the Atlantic. Vertically it extends beyond 2000 fathoms up to 5000 fathoms and gives way to red clay at greater depths.

(iv) *Diatom Ooze*. This name was first given by Murray, in his Challenger report. It is formed of the plant shells very microscopic in size. The shells are mostly made of silica. It is yellowish or cream coloured and turns into fine, white, coherent powder when dried up. Near the land its colour is blue. Within the diatom ooze other substances such as remains of sponge spicules, radiolaria skeletons and amorphous, clayey constituents are also found. The calcium contents range between 3-30%.

The area of occurrence of this ooze is in high latitudes in both the hemispheres. In the Antarctic Ocean south of 40° S it forms a broad band and here it covers $10\frac{3}{4}$ million square miles of area. Another girdle in the North Pacific covers 40,000 sq. miles. Vertically the ooze is found between 600-2000 fathoms, though it may also extend up to 4000 fathoms in special areas.

4. INORGANIC PRECIPITATES

Changes in the nature of atmosphere and sea take place as a result of temperature changes or removal of carbon dioxide or greater precipitation. Thus various inorganic precipitates fall in various parts of the earth far away from their source. These precipitates are never abundant. They include dolomite, amorphous silica, iron, manganese oxide, phosphate and barite etc. Along with the inorganic precipitates such products are also found in the sea which are subject to chemical transformation, namely, glauconite, phosphorite, feldspar, phillipsite and clay minerals. It is very difficult to distinguish between inorganic and organic sediments due to the chemical decomposition.

5. RED CLAY

It is perhaps the most widely spread pelagic deposit. It consists mainly of hydrated silicate of aluminium and oxide of iron. It was first thought to be produced by disintegration of land. Wyville Thompson thought it to be an organic deposit, that is, a residue of the insoluble calcareous organisms. It could also have formed from chalk brought from the land. But according to Murray it is a result of chemical decomposition of aluminous silicates and other sub-oceanic rocks. The nature of the clay is soft, plastic, and greasy. When dried, it becomes a powder of reddish-brown tinge. The red colour is given by the presence of oxide of iron.

Apart from the above, red clay consists of decomposed volcanic material floating in the sea. It is abundant near the volcanoes, otherwise it is rare. However, other rare materials such as earbones of whales, teeth of sharks, phillipsite, manganese-iron nodules etc. are also found in it, especially because the red clay is found at the depths of 2700 fathoms and more and as the rate of deposition of clay is slow.

Among the minerals, it contains calcium (6.70%), siliceous organisms (2.39%), minerals (5.56%) and fine washings (85.35%) (hydrated silicate of alumina). Radioactive substances are mostly found and recognised in the red clay, more than in other marine deposits.

Red clay is found in almost all the oceans in their deepest parts. In North Atlantic, the colour is brick red and in the Pacific and the Indian Ocean it is dark chocolate. Sometimes red clay also occurs in the North Polar Basin. It covers an area of about 50 million square miles.

6. EXTRA TERRESTRIAL MATTER

Though this type of material is rare, yet it is of immense interest. It constitutes of meteoric dust coming from the space recognised as "cosmic spherules" and has black or brown colour in microscopic size. It usually consists of iron or magnetite of iron oxide and is found only in deeply laid deposits accumulating slowly.

CLASSIFICATION ACCORDING TO LOCATION OF DEPOSITS

Murray has classified the sediments according to the areas in which they are found, commonly known as terrigenous and pelagic deposits.

There is a clear distinction between the terrigenous and the pelagic deposits. The former is the result of disintegration of continental rocks, brought down by various transporting agencies and deposited on the continental shelf and slopes, whereas the pelagic deposits are mainly formed of skeletons, shells, and some inorganic substances, found deep into the seas. Pelagic deposits are found to be light coloured (reddish or brown) and fine grained, whereas terrigenous deposits occupy a wide range in depth and great variation in colour, texture and composition. The colour ranges from blue, yellow to red and the texture is usually coarser. Coral mud or sand can deposit around such islands by mechanical action.

TABLE 2¹
Marine Deposits

1. Deep Sea deposits (beyond 100 fathoms line).	A {	Red clay Radiolarian ooze Diatom ooze Globigerina ooze Pteropod ooze	Pelagic deposits in deep water remote from land.
	B {	Blue mud Red mud Green mud Coral mud Volcanic mud	
2. Shallow water deposits (low-water mark to 100 fathoms)	Sands Gravels Muds		Terrigenous deposits in deep and shallow water close to land.
3. Littoral deposits (between high and low water)	ditto.		

There is no clear cut boundary between these two sediments, as the terrigenous deposits may encroach the territory of deep sea deposits near oceanic islands, volcanoes, ridges and plateaus etc. Similarly on the shelf, remains of plants and animals are found in abundance. Wherever these are not covered by terrigenous deposits, they are visible. Thus both deposits are mingled with one another, yet a demarcation line of 100 fathoms is formed on the basis of predominance of a single type of material.

As we have seen before, the nature of these materials also varies according to the depths of the ocean. The terrigenous deposits contain inorganic elements in abundance, specially, quartz sand etc. due to the nearness to the land, while the amount of calcium carbonate in the pelagic deposit disappears with the increasing depth due to its soluble nature. Hence Globigerina and Pteropod contain higher calcium than red clay and diatom ooze. At the bottom siliceous material predominates as it is insoluble.

Another classification of sea bottom deposits is rather more illuminating and is as follows:

- | | |
|--|--|
| 1. Continental deposits or Terrigenous deposits. | Littoral deposits;
Shallow-water deposits;
Terrigenous muds. |
| 2. Neritic deposits. | Shallow-water neritic deposits;
Oceanic neritic deposits. |
| 3. Pelagic deposits. | The deep-sea oozes. |

¹ Jenkins, J. T., *A Text Book of Oceanography*, p. 23.

CONTINENTAL DEPOSITS

Here at least 66% of the deposits are formed of minerals such as quartz. They are further sub-divided into the following categories:

Littoral deposits. The deposit extends up to 1000 m. and according to Kuenen up to 2000 m. The littoral deposits are confined below the high and low tide line. According to Murray and Renard it is the material which is deposited on the foreshore. They consist of mainly boulders, gravels, sands etc. and also mud which is only found in sheltered bays. In this part of the sea, large number of organisms and plants are found along with coral reefs and mangrove swamps. Hence the occurrence of Mollusca (cockles), Crustacea (crabs), Echinoids, and worms is not rare. The eroding agent is mainly waves, whose level of attack changes with the high and low tide. During storms sometimes coarser material is high on the beach, or along the shore, and comparatively smaller material is transported at low tide level. The sediment that is laid here arranges itself according to size, and their nature is determined by the features of the adjoining land. If the material is hard and the coast is rocky, small terraces would be found. But if the land is flat and undulating, the material from land would be equally distributed. Wherever land is easily eroded, the littoral deposits do not show gravels and boulders, but loose sand is visible at the upper end of the foreshore. According to Martens these sediments are of varying size. Only near the river mouths they are fine and well assorted. The organic siliceous remains are never present in this sediment but organic calcareous shells are found, wherever deposition from land is slow or absent. Beach deposits have been widely studied by Martens (1939), Schalk (1938), and Hantzschel (1939), who attribute the lateral variability of these sediments to the sources, localities of the constituent materials and the relative intensity of waves and current action. Russel and Twenhofel have marked a difference in deposits near the Mississippi mouth and the open ocean. The texture in the basins also varies. But it is generally fine. Littoral deposits cover about 62,500 square miles of area in the oceans.

Shallow-water deposits. This deposit extends from the shore up to 100 fathoms. The main source of the sediment is in the land nearby. Hence, stone, boulder, gravel and sand are abundant, though mud is also not of rare occurrence.

Along the shore strong currents and waves are found, hence transportation of sediment is rapid. According to Shepard, Rip currents contribute to the removal of sediments from the beach. Disintegration and decomposition of the sediments take place and only more resistant species remain. Thus quartz is again the important element here.

This zone is equally suited to receive the material from the land or from the volcanic explosions. In low latitudes, only high organic calcareous detritus is found in this zone. There is of course a great range in the size of particles, from the mud to the gravel. Many observations by Shepard, McDonald, Stetson, etc. show that along the Pacific coast and the Atlantic coast there is a marked decrease in the median diameter of a particle, in a shallow water, within a few hundred feet of shore, though no correlation exists between the size of the particle and the depth of the bay. Murray and Renard estimated that it occupies 10 million sq. miles of sea surface.

This characteristic of the sediments leads to the gradation of the shallow water deposits. The effect of the waves is felt most strongly on the beach itself, than on foreshore and finally on shallow water bottom. Hence there is a sorting of the sediment also. Coarser gravels and boulders are found near the coast, which gradually give way to finer sediment sand and clay, as we go downwards. Sometimes due to land slides, strong eddies and waves or storms, this stratification is disturbed.

Terrigenous Muds. As we have seen before, various types of muds are found beyond 100 fathom line. It contains elements which are responsible for their colour. These particles are still finer than that of the sand particles.

NERITIC DEPOSITS

The Neritic deposits consist of the organic shells and skeletons of various animals and plants which are not restricted to any particular sea bottom because of the universality of animal and plant life in the sea. The principal shallow water Neritic deposits are shelly gravels and sand found at 50 fathoms depth. The remains are mainly valves of bivalve and univalve shell-fish, nullipores, gravel and sand, which are known as calcareous algae, shells of molluscs, specules of sponge, plates of echinoderms and polyzoan gravels and sands which are colonial animals of small size, forming thin crust on the surface of the terrigenous material. Their deposition takes place with the help of tidal streams, currents etc. which carry the eggs in this region. Thus neritic deposits vary according to the local peculiarities of the sea, namely, the temperature and the salinity of the water, direction of the current, etc.

The deep water or oceanic neritic deposits occur around the oceanic islands. There the main characteristic is the absence of continental shelf and only volcanic sand and mud forms the bottom to some extent. Among such types of deposit, coral formation (animal belonging to Hydrozoa) is worthy of note.

PELAGIC DEPOSITS

Johnson states that three categories of Pelagic deposits are found: *Benthos*—all rooted, sedentary or semi-sedentary organisms, include corals, sponges, polyzoa, starfishes, sea-urchins etc. and are found attached to sea bottom or sand or mud. *Nekton*—the marine mammals which can swim freely in waters and have more developed locomotory organs and calcareous skeletons. *Plankton*—including all unicellular plants (Protozoa, Diatoms etc.), all smaller crustacea (amphipods) and marine worms. The last one also include various oözes found on the ocean bottoms.

Pelagic deposits cover about 75.5% of the sea area. Here the change from one type of ooze to another is rather gradual and overlapping. Red clay, which is also a pelagic deposit but an essentially inorganic one is found at the greatest depths. Table 3¹ gives the areas of oceanic deposits in percentage.

¹ Jenkins, J. T., *A Text-book of Oceanography*, p. 25.

TABLE 3

Types of Deposits	Area Percentage
Littoral and Shallow water	9.1
Deep Sea deposits (Terrigenous)	
Pelagic	15.4
Globigerian ooze	29.2
Pteropod ooze	.4
Diatom ooze	6.4
Red clay	36.1
Radiolarian ooze	3.4
	75.5
	100.0

OTHER CLASSIFICATIONS

Another scheme of classification divides the marine deposits according to the origin of the constituents of the deposits.

- | | |
|--|--|
| 1. Littoral (derived from land) | Shore deposits
Shelf deposits |
| 2. Hemipelagic (partly of land, partly of marine origin) | Green mud
Volcanic mud
Coral mud |
| 3. Eupelagic (marine and cosmic origin) | Red clay, Radiolarian,
Diatom, Globigerina and
Pteropod ooze |

Monkhouse has in his division of marine sediments included Bathyal zone, as shown in Fig. 31, which occurs on the continental slope and contains muds etc.

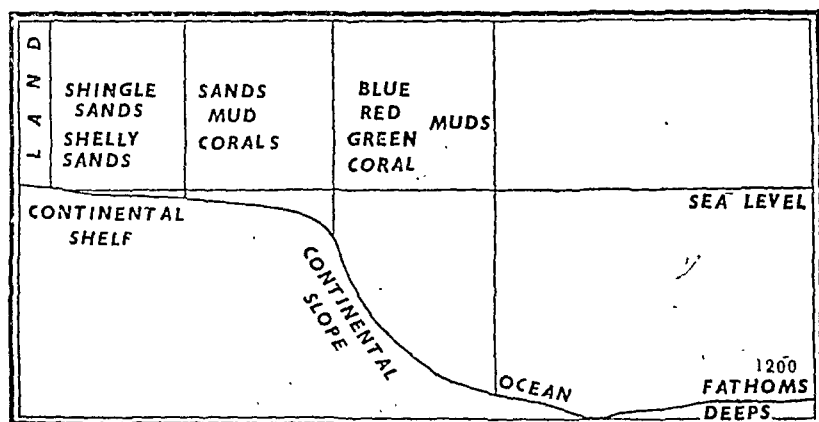


Fig. 31. Generalized profile of the ocean floor, showing the general distribution of marine deposits.

(By permission, from *The Principles of Physical Geography* by F. J. Monkhouse. Copyright 1954. University of London Press Ltd.)

Another classification takes into account the colours of the marine sediments, which depends on the amount of moisture, primary colour of the grain, the state of division (size), oxidation, and the amount of decomposable organic matter. Ridgway (1912) has made a chart to show the colour of various sediments. Generally marine sediments vary from white through grey to black in their colour scheme. Coarse grained deposits composed of quartz and limestone usually have white colour. Black deposits having iron contents are found in stagnant fiords and basins. River borne debris is generally found to be yellow, red or brown. Large quantity of organic material present in the sediment makes it black or brown.

TRANSPORTATION OF MARINE SEDIMENTS

Marine sediments found at the bottom are deposited by the transporting agencies. Twenhofel (1932) discussed about the agencies which transport the material. They are—

1. *Rivers.* These are perhaps considered to be the main agents which help to bring the disintegrated rock particles upto the sea and deposit them on the shelf. Various types of coloured muds and the nature of the shelf signify the role of the rivers in the process of deposition. By them a variety of terrigenous material, ranging from sedimentary to igneous, from red to black, and from big to small, is brought into the sea water. They carry down thirty-three times as much sediment as worn off the coasts by waves.

2. *Rain wash.* It causes most of the landslides, occurring along the river banks as well as slidings along the coasts. Landslides occurring on the heads of submarine canyons also help to widen their valleys on the shelves and carry the sediment farther into the deep sea. Thus a vast amount of sediment is being deposited.

3. *Erosion by waves.* The mighty waves erode the land along the shores and break it into fragments and boulders which are further reduced to sand and mud. They also carry the particles, far away from the shores; and only along waveless coasts or rather quiet areas, these sediments are deposited.

4. *Work of ice.* The work of glaciers is of great importance in higher latitudes. They carry with them like river water, whatever debris they come across either by erosion, plucking or by disintegration. According to Twenhofel, in the Arctic Ocean, shallow water sea ice is formed during winter, capturing within it the sea bottom material present there. Due to melting of ice, the surface of the icebergs would rise and float away, thus the material is carried far away from the source. This material, as deposited ordinarily or during glacial ice age, is characterized by a variety of debris, ranging in size and in character depending on the rocks. Murray and Hjort (1912), Bramlette and Bradley (1940) have also noted icebergs carrying land debris far away from the source. After they melt away from the land, the glacial material is deposited along with the pelagic deposits.

5. *Organic rafting.* Small amounts of debris is transported by trees, vegetation etc. which during the floods float and carry themselves to a

character of the sea water, has an important effect on deposition. The temperature of the water controlling the living organisms, hydrostatic pressure (a function of depth) and the water content of sediments are probably among the foremost factors. Trask and Pettijohn discussed about the porosity of the sediments, depending on texture, shape etc. which controls the rate of deposition. To some extent, salinity also influences solution and precipitation of calcium carbonate. Calcareous material and its percentage varying according to the depths perhaps shows the peculiarity of its distribution. Table 4 (after Revelle 1936) shows the calcium content in the Pacific.

The general rate of sedimentation for all the deposits is extremely small in the open ocean, that is, less than 1 cm. per 1000 years, as estimated by Kuenen (1937).

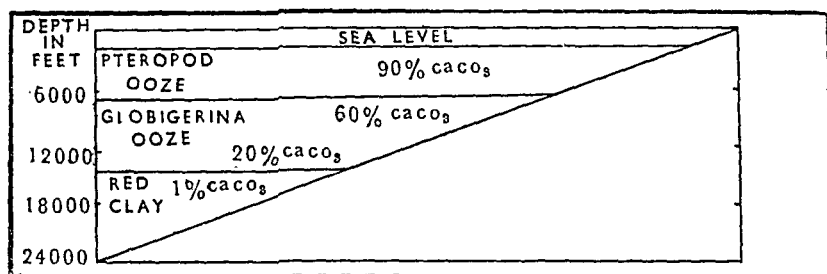


Fig. 32. General vertical distribution of ocean deposits showing the decrease of lime (CaCO_3) with the increase of depth. (After Murray).

TABLE 4¹

Average Percentage Calcium Carbonate content of the Pacific Ocean Pelagic Sediments

Depth (in meters thousands)	Latitudes									
	50-40°S	40-30°S	30-20°S	20-10°S	10-0°S	0-10°N	10-20°N	20-30°N	30-40°N	40-50°N
0-1						41.0				
1-2			94.0	74.4	75.0	38.4				
2-3	62.0	74.7	63.5	65.9	68.0	57.8	32.5	18.0	22.0	
3-4		63.6	53.4	72.3	54.0	49.4	0.6	11.7	56.0	6.0
4-5	37.5	18.8	17.9	19.9	47.5	55.9	17.6	1.9	1.8	
Greater than 5			0.0	16.0	10.7	24.7	1.0	0.8	0.6	0.5

¹ *Ibid.*, p. 1005.

It is by two methods that the rate of deposition is calculated, i.e. *the stratigraphic* method by estimating the total thickness of sediment in the given or total time; and *the supply* method which lays stress on the amount of material available or supplied in the given time. The former is well suited for individual area, while the latter is for general area. There may be difficulties in the study of the data due to changes in the level of the area, difference in the rate of accumulation, difficulty in getting cores, and in estimating the material derived by volcanoes and air.

Computation regarding the rate of deposition could be based on the material derived by rivers only. According to Schuchert (1931) the following is the rate of sedimentation in shallow water derived by stratigraphic method.

Sandstone.....68 cm/1000 years

Shale.....34 cm/1000 years

Limestone.....14 cm/1000 years

It is however known that in more shallow water rates of accumulation are much greater than that in the open sea. Schott (1937) computed the rate of deposition in equatorial Atlantic, according to the core sample for different oozes. The average value for blue mud, globigerina ooze, and red clay amounted to 1.78, 1.2, 0.86 cm per 1000 years respectively. Braun pointed out 0.59, 0.54 per 1000 years as the rate of deposition of globigerina and diatom ooze in the South Indian Ocean. Here, the rate of globigerina deposition is $\frac{1}{2}$ of the deposition rate in the equatorial Atlantic.

According to the estimate based on the supply method, Clarke (1924) remarks about the rate of 'chemical sedimentation' that the sodium and chlorine escaped the deposition, but otherwise, the chemical deposition by rivers is between 22×10^3 and 24×10^3 metric tons. If it is distributed evenly it would form a layer equal to 0.25 cm/1000 years. Kuenen and Cambrian estimated the rate of terrestrial deposition (taking 500 million years' deposition), chemical as well as detrital, to be 0.33 cm./1000 years in general and 0.1 cm./1000 years for red clay, and 0.2 cm./1000 years for globigerina ooze. The floor of the Atlantic and the Pacific is being built at the rate of 1 inch/20,000 years and 10 inch/20,000 years respectively.

In the end it should be noted that the values given, in general, may appear somewhat greater for the ocean deeps where deposition rate is actually too slow and lesser for the shallow areas where deposition rate is faster. However, it must also be kept in mind that large variations occur all over the oceans.

DISTRIBUTION OF SEDIMENTS

VERTICAL DISTRIBUTION

Various samples of bottom deposits show a stratification in their distribution. Philippi examined the sediment during 'Gauss' expedition and

says that stratification is the rule of bottom deposits. The difference in the colour, from blue in its lower portion to reddish brown in the upper portion of the same layer, has been noted and attributed to ferric oxide changing into sulphide oxide in deeper layer. Generally the vertical range of distribution of pelagic deposit is in a series ranging from Pteropod ooze¹ (on shallower bottoms) to globigerina, radiolarian and diatom ooze and to red clay (at deepest bottoms). To some extent this vertical distribution depends on the solution of the calcareous materials. The sorting out takes place in the ocean in which calcareous material is easily dissolved.

Thus only siliceous material such as Radiolaria, Diatom, and sponges, would be dissolved at greater depths, hence they occupy the bottom deposits. At the deepest bottom red clay is found, which is formed of inorganic substances such as volcanic materials, whereas calcareous shells, pteropods and globigerina should be found at lesser depths.

HORIZONTAL DISTRIBUTION

The world map would show the general pattern of distribution of marine sediments. Terrigenous deposits are found almost all along the coast but they are specially greater in extent near the East Indies, the North Pacific, and the Labrador coast. The Indian Ocean is marked by Globigerina ooze mostly on the western side, whereas southern and

TABLE 5²
Areas covered by Pelagic Sediments (Million km²)

	Atlantic Ocean	Pacific Ocean	Indian Ocean	Total
<i>Calcareous Oozes</i>				
Globigerina	40.1	51.9	34.4	...
Pteropod	1.5	...	...	...
Total	41.6	51.9	34.4	127.9
<i>Siliceous Oozes</i>				
Diatom	4.1	14.4	12.6	...
Radiolarian	...	6.6	0.3	...
Total	4.1	21.0	12.9	38.0
Red clay	15.9	70.3	16.0	102.2
	61.6	143.2	63.3	268.1

 Shells of Pteropods are thinner and easily dissolved. Hence they do not extend up to Globigerina which lives in cold water and is absent in shallow muddy water. Thus the former is found only in sub-tropical region, whereas the latter is found in both regions—temperate and tropical. Radiolaria or Diatom are siliceous, therefore they are not easily dissolved, and found in deep water. The former lies in the tropics while the latter near the poles.

² Svedrup and Others, *The Oceans*, p. 977.

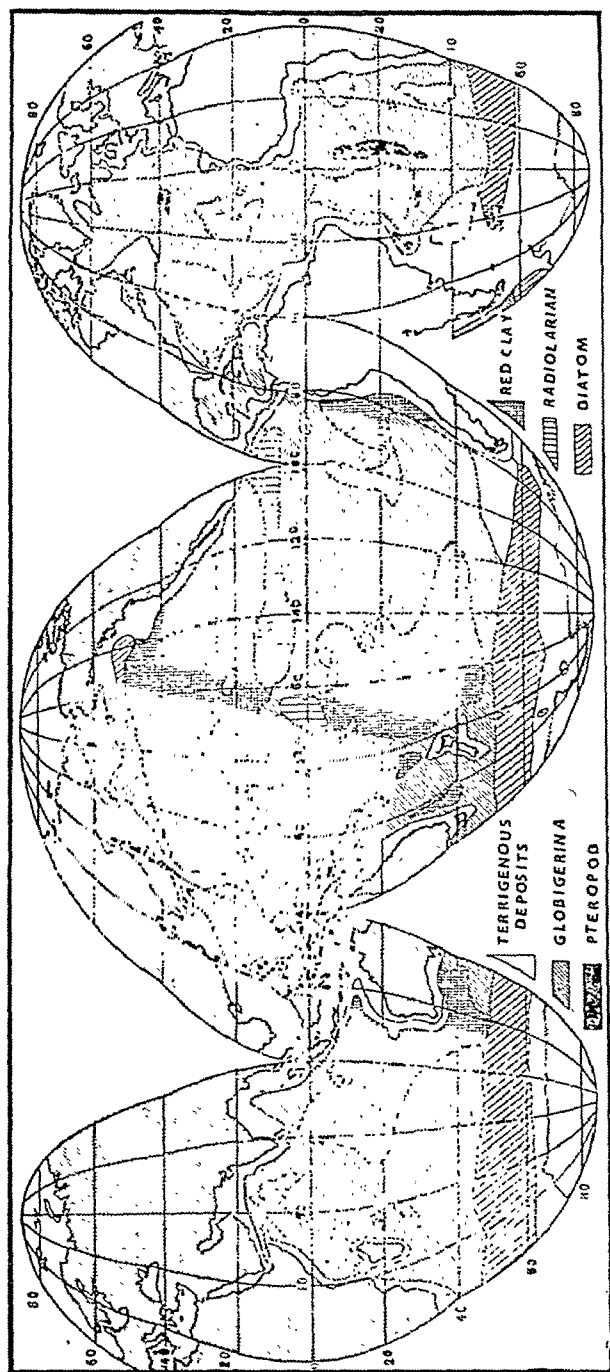


Fig. 33. World distribution of pelagic deposits.

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eastern parts have Diatom and Red clay respectively. Patches of red clay could be noted in the Atlantic from north to south, embedded in Globigerina ooze. In the southern part similar layer of Diatom ooze extend between 50° S— 60° S. The Pacific is perhaps the most complex ocean regarding the distribution of deposits. Diatom layer is found in the southern Pacific and in the north-east Pacific. A layer of Radiolarian ooze extends between 15° to 5° N and 160° to 90° W. Most of the north Pacific has red clay deposits, while the south has globigerina ooze.

Chapter 7 | CORAL REEFS AND ISLANDS

Coral reefs and atolls, one of the important features of surface topography, have deep connections with the bottom of the ocean. At certain places, they do not appear even above the sea level but remain attached to the submarine platforms and islands under the sea. Coral reefs are confined in a zone between 25° N— 25° S and form distinct relief feature of the tropical seas. They usually attach themselves either along an island or shore that is different from the corals, or they form separate islands into seas far removed from the land.

These coral reefs are masses of limestone and dolomite accumulated by lime-secreting organisms known as coral polyps—a kind of fleshy anemone—which are green, yellow, pink, violet and white in colour. Each individual polyp consists of tentacles, mouth and stomach. In their tissues there live myriads of microscopic single celled plants which supply food to polyps. This association between plant and animal is called symbiosis and helps in the formation of reefs. "Some of the corals live apart in their cup-shaped depressions; but their habit of forming colonies, among true reef builders, results in growth with such luxuriance and abundance that neighbouring colonies fill up all the available space and become welded together in a solid mass of coral rock".¹

The cementation and coalescence of corals is partially due to the solution and reprecipitation of the calcareous sand, but mostly due to the work of other calcareous organisms and algae. The remains of calcareous organisms are molluscs, echinoderms, foraminifera and other lime-secreting organisms and the algae are halimeda, lithothamnion, nullipores etc. They live in between the spaces of coral branches and thus also enter into the composition of the coral reefs. Sometimes broken coral material is also incorporated into the reef, but the work of coral polyps remains most dominant.

CONDITIONS OF GROWTH

☞ In spite of their profusion in tropical waters coral polyps restrict themselves to certain areas because of their conditions of growth. One of the prime requisites for the development and occurrence of coral polyps is the temperature of the sea water. It should be between 68° – 70° F, hence they avoid too cold and too hot waters of extreme regions of the oceans.

☞ Corals usually do not live in water more than 200—250 feet below sea level, because up to this depth bright sun light and oxygenated

¹ Colman, J. S., *The Sea and Its Mysteries*, p. 153.

matter helps the photosynthesis of the plants and the symbiotic living of corals. Only a few scattered colonies of the corals may spread below this depth. M. S. Ladd and J. E. Hoffmeister (1936) estimated the depth between 200—300 feet as the maximum up to which corals could grow. Gardiner has referred about some deep sea corals thriving at 150 or 170 fathoms but these do not have green plants in their tissues.

(3) The living corals also demand a sediment free water, as turbidity appears to be the most important factor limiting their growth. This is because sediments clog the mouth of coral organisms and cause apaqueness which inhibits symbiotic metabolism by which corals take their oxygen. Hence the coral dies and the growth of the reef is stunted. Sometimes broken coral reefs are also found in front of the debouchures of rivers which bring ample of sediment. On the contrary, in some cases we find coral reefs growing in the proximity of certain river mouths as in Hawaiian islands, Indonesia and part of river Loza in Madagascar. Similarly, there is a luxuriant coral growth in the Great Barrier reef of Australia in spite of the water being muddy. In this connection P. Lake remarks that "a slow but more or less continuous supply of sediment is far less destructive than a sudden influx."¹

(4) High saline water is also injurious and uncongenial for coral growth due to the lack of carbonate of lime in it which is the main food of these organisms. Hence the average salinity should be between 27% and 40%.

(5) Again, fresh water is also harmful and kills the coral polyps. To avoid this, corals mostly grow far off from the coasts and particularly away from the river mouths. For example, the Great Barrier reef of Australia is found to be broken in gaps at places where rivers pour fresh water into the sea. Nevertheless, rain water also checks and kills the coral polyps that are found above the low water. "An interesting case of the effect of fresh water on a reef occurred at Stone island near Bowen, Queensland. This island possesses a fringing reef which was exposed to a rather unusual extent by a low spring tide. At the same time, there was a torrential rainstorm, the effect of which was completely to kill the corals, though, perhaps, some allowance must be made for the effect of exposure. However, Hedley, who examined the reef, concluded that the rainstorm had the chief effect".²

(6) Observations of coral reefs reveal that polyps cannot live above the sea level. Due to the work of winds and waves, erosion of the surface is active and the sand is distributed over the reef which kills the polyps. So even those reefs, which are not elevated but are occasionally exposed above the low tide level, have dead reefs over their surface. Hence, living corals are found either in depressions or towards the outer margin of the reef into the open seas.

(7) The disturbed water and the currents of the oceans are not destructive for coral growth as their hard surface is used to the wave attacks. On the contrary, it brings food supply and oxygen for the polyps. Lagoons, the enclosure of the sea water between land and the reef, do not have living coral polyps, though the bed and sides of the lagoon

¹ P. Lake, *Physical Geography*, 1958, p. 205.

² J. Steers, *Unstable Earth*, 1950, p. 269.

is made of dead corals because here the water is motionless and the food is scarce. Moreover, the action of the wave has great effects in shaping the growth of the corals. In calm sea waters they develop branches like the stag's horn. But violent wave action breaks off the tips of the branches and leaves rounded masses of coral reefs.

The last but not the least important condition for the growth of a coral reef is the existence of a submarine bench or a platform on which corals start their colonies. Observations show that coral reefs start on a strata as old as Cambrian and in calm seas like Red Sea even on the unstable base of sand. These platforms must be within 50 fathoms depth either along the shores of the continent or along an island in an open sea. Those polyps which find such resting places start their colonies at the bottom of the reefs after taking a firm base on the continental hard rock. Usually, the growth of the corals is below the low tide water level but away from the land border it is upward the sea level. Only occasionally they are exposed above the sea surface when the reef is covered by coral debris brought by the waves. Apart from the upward movement, the coral reef spreads outward due to the abundance of food gained in the open sea. The outward growth determines the width of the coral reef. Consequently, a shallow water lagoon develops, as the coral polyps on the landward side of the reef are killed due to excess of sediment in the motionless water of the lagoon. The width of the lagoon increases with the growth of the coral reef and its bottom is changed by debris from the land.

TYPES OF CORAL REEFS

All the coral reefs found in the oceans do not resemble in kind and shape. They can be divided into two broad categories : (i) According to their nature and mode of occurrence, and (ii) according to the location of corals.

ACCORDING TO NATURE AND MODE OF OCCURRENCE

Fringing Reef. Under suitable conditions in the sea the narrow belt of reef growing from the deep sea bottom along the steep shores of landmass is known as the fringing reef. These reefs may develop around islands. Their growth is interrupted where big rivers flow into the sea. The width of the reef is comparatively narrower and the seaward edge is slightly



Fig. 34. Fringing reef.

higher than the landward portion. Its surface forms a rough and fissured platform about the level of the low water, as here waves deposit the fragments of corals in the form of a boulder zone, commonly known as the *reef flat*. Occasionally, the fringing reef is separated from the shore

by a narrow and shallow lagoon having a depth between 0.3 to 1.5 m. known as *boat channel*. Such channels are found in Madagascar and Red Sea (north of Jiddah). But usually as the reef is a thin veneer of coral closely attached to the shores, so it leaves no chance for the formation of lagoons. Again, due to sharp increase in the depth along the shores, there is comparatively lesser accumulation of talus. Hence there is a small foundation for the outward extension of living corals.

Fringing reefs are of two types: those which face the open ocean and those which are protected by a barrier. Examples of fringing reefs are afforded by Sakau island of Maskelyne island in New Hebrides, Southern Florida reef, and Mehetia island. The last is an island in Society group of islands. A young volcanic cone, as it is, has moderately developed cliffs around the islands. A young fringing reef grows along it after subsidence has taken place.

Barrier Reef. It is perhaps the largest and the most extensive of all the reefs. It is composed of myriads of corals of all sizes clustered over the coastal platform. The surface contains boulders, coral debris and sand deposits. The outward slope of the reef seems to have 45° but in a few cases it only ranges between $15-25^\circ$. The reef itself grows from the deep bottom and lies at a much greater distance from the coast. Hence

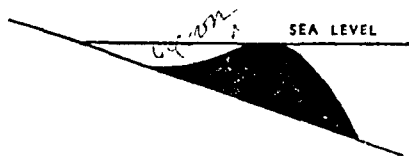


Fig. 35. Barrier reef.

a shallow and broad lagoon develops between the reef and the shore as shown in Fig. 35. The immense thickness of the coral found in a barrier reef presents difficulties regarding its origin as the lower part of the coral base extends much below the necessary depth of 30 fathoms. The upper exposed part of the reef is several miles wide, which is interrupted by innumerable channels forming an easy sea passage into the lagoon. Sometimes the reef extends uninterrupted for hundreds of miles broken only by big rivers which bring great amount of fresh water and debris in front of the reef. In a few cases islands are also found in between the lagoon, and the encircling reef is in the shape of a circular mass.

Great Barrier Reef of Australia is the most famous and largest of all the barrier reefs. It stretches on the eastern side of Australia from 9° to 22° S. (from Torres Strait to Swain Reefs) for about 1200 miles, thus covering two-third of the length of the Queensland coast. The Barrier Reef is separated from the main land by a flat-bottomed and shallow lagoon. In northern half it is 80 miles away from the coast, in south, near Cape Melville, it is only 7 miles apart. In between these two the distances vary from 20 to 30 miles. South of Cairns, its distance from the shore increases. Off Townsville it is 50 miles apart, whereas Swain Reefs which are part of the Great Barrier Reef, though considered separate from it, are nearly 100 miles off shore.

[The shallow lagoon is nearly 40 fathoms deep and from 7 to 80 miles in width.] The width and the shape of the lagoon varies with the nature of surrounding reef. Occasional exceptions of deep water are found in the lagoon near high islands. The depth also increases gradually from the coast to the outer margins where the average depth in steamer channel is between 15 and 20 fathoms. Flat floor of the lagoon is explained as the outcome of deposition of sediments derived from the main land by rivers.

[The reef itself is quite wide, but made up of a series of individual reefs spread over the platform.] It changes much in size and shape and usually has crescentic form, with the "ends" of the reef turned landwards. The outer northern reefs are long and narrow, parallel to the coast, e.g. Ribbon Reef is 14 miles long with a well defined edge dropping to 1000 fathoms. The southern reefs are isolated and cut by narrow and tortuous channels. The inner reefs growing up directly from the floor of the lagoon are also isolated and parallel to the Great Barrier and the mainland. They also vary in size and have deposition of sand and clay on the leeward side. Out of the important reef openings in the north, Trinity opening is an important one. Island reefs or low wooded islands are also not rare in the steamer channel.

Atoll. It is a ring of narrow growing corals resembling horse shoe around an island or on submerged plateau and crowned with palm trees and often hundreds of miles away from any continental land. It rises abruptly from the deep sea platforms upto the sea level. In the middle of the coral ring, sometimes broken on one side, lies a shallow lagoon



Fig. 36. Atoll.

of open water ranging in depth from 40 to 70 fathoms. According to their nature, atolls can be divided into three types: (i) the true atoll with a circular reef enclosing a shallow lagoon and having no island in it; (ii) the type of atoll which possesses a central island in the lagoon, around which the reef is found; and (iii) the last type, known as coral island or atoll-island which is in fact an atoll reef but by the process of erosion and deposition of waves island crowns are formed on them.

The shape of such atolls is oval, with the major axis orientated according to the wind direction. In Indonesian reefs, due to changing directions of the monsoon, the form of the reef changes. The depth of the lagoon (a pseudo lagoon or swamp) is few metres only, whereas the bottom is covered by black calcareous mud and sand. Such reefs are very common in epi-continental seas such as Indonesian seas, the south China Sea, the Antilles, the Red Sea, and in Australian Sea around Great Barrier Reef and along north west coast of Madagascar. Such small reefs are associated with tidal currents, e.g. reefs between Cape Direction and Cape Melville on Queensland west.

The process of formation of coral island starts with the production of finer material by wave action which breaks down the living corals or the coral boulders. By and by more material will be deposited in the windward side along the boulders and it is cemented in between the interspaces by the action of sand and carbonate of lime. Similar accumulations along the rim by storm and wave action would form a discontinuous crescent shaped ring of breccia material. And the fine sediment would be transported and distributed on the other side of the ridge and platform would be formed. On this actually sand banks and sand cays would appear. "The slackening of the currents on the reef flat, and the force of the waves on seaward side of the obstruction, cause the resulting island to be narrow and crescentic in form." The development of the island depends on the sand supply, otherwise they remain piles of broken corals and coral boulders. Sand is mostly carried to the leeward side where sand banks and low wooded islands are formed. The latter is the result of the deposition of various seeds in sand brought by the waves. This process continuously shallows the lagoon. When mangrove swamps grow along the boulder zone, it is known as low wooded island.

Various atolls, e.g. E. Fiji Atoll and Trunk Atoll of West Carolinas, are found in the Pacific. Among coral islands, the cays are found in the Bay of Batavia, Java and also along the Queensland coast, e.g. Sudbury Cay, Green island off Cairns, Bunker and Capricorn island and Beaver Cay; the low wooded islands¹ or Island reefs are found in the northern part of the Barrier reef.

Funafuti Atoll. It is considered one of the important atolls of Ellice Island. It extends in north-north-west and south-south-east direction along 176°66'E from 11° to 5°30'S. It is the largest island having 6½ miles length and 600 yards width at the maximum. And on the eastern side of the reef are islands varying from 50 to 300 yards in width. The shape of the Atoll resembles the caricature of the human head. The enclosed lagoon is 8 miles broad and 12 miles long. Its depth is between 20 to 25 fathoms though shoals are also recorded in the lagoon. 'The reef around the lagoon is not continuous: the longest unbroken stretch runs from Pava Island in the north of Funamanu on the south-eastern side of the lagoon.' The atoll seems to arise from 2000 fathoms depth and the shape of the island is controlled by its rocky foundation, growth of plants, prevailing winds and currents.

ACCORDING TO LOCATION OF CORALS

Tropical Coral Reefs. The coral reefs in the warmer waters are confined within 25° N—25° S where they grow in abundance. They are mostly circular in form, with the height above the sea level ranging between 100—400 ft. Their shores are irregular and embayed.

¹ The difference between the sand cays and the low wooded island or island reefs should be made clear. Former are merely a heap of coral sand, eroded from the reef and piled up by the wave action on the leeward side of a reef. They are usually devoid of vegetation and are flattish. Cays are absent from poorly developed reefs while the latter, situated mostly in the steamer channel, have two regions. On the leeward side is the sand cay, and to windward is the single ridge resting on the platform of coral rock enclosing a low conglomerate platform, a high conglomerate platform, dunes, and mangrove swamp. In between these two is the reef flat.

Most of the reefs are found on the eastern shores of the continents. Masses of coral may occur, but they do not form typical reefs on the western coasts of either America, Africa, or Australia. It is the zone of the trade winds and the western side is the leeward side where there is an

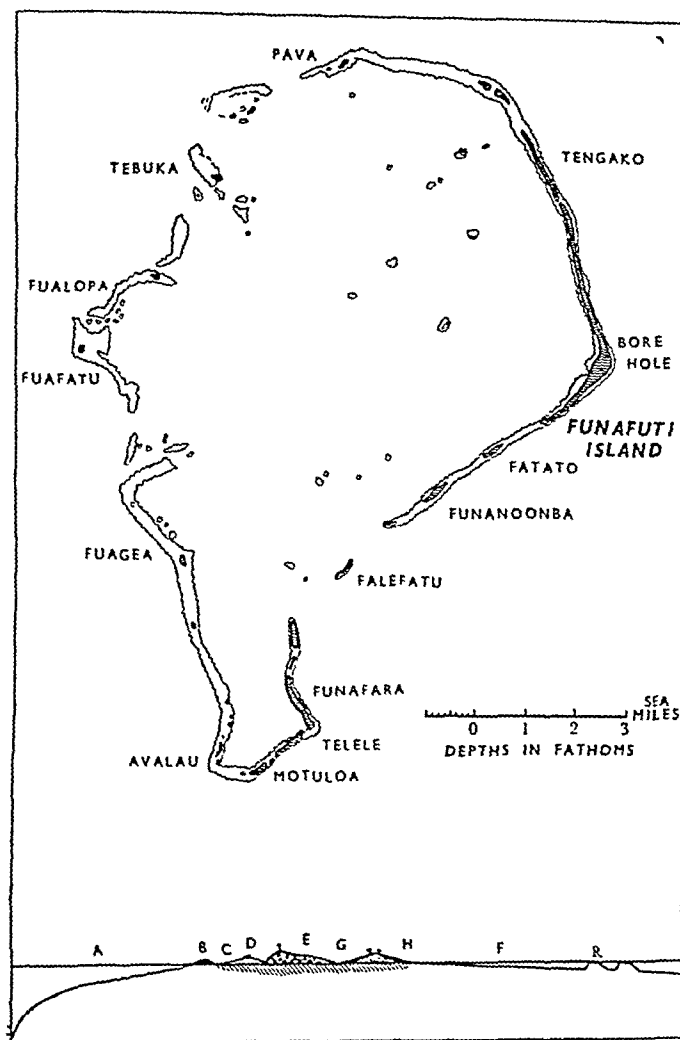


Fig. 37. Funafuti Atoll and its Diagrammatic Section (after Daly).

A. Constantly submerged portion of the reef; B. Nullipore rim; C. Reef-flat of coral rock; D. Ledge of coral rock; E. Seaward or outer ridge; F. Floor of lagoon; G. Central flat of islet; H. Lagoon mound; R. Growing reefs of lagoon.

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upwelling of cold water. Probably this is the principal cause of the absence of reefs in the western part of tropical seas. But it cannot be the sole cause, for near the equator even on these shores, the surface water is warm enough for corals.

Coral reefs are especially found in the central and western Pacific Ocean where the normal rate of growth of reefs is between 6 and 8 feet per century and Pacific reefs, according to A. G. Mayer, have grown in 30,000 years. He also calculated that this rate of growth in the Pacific is about twice of the growth rate in the Atlantic where food conditions are unfavourable. He found at Samoa that present rate of growth of corals add 840,000 lbs of limestone to the reef annually but 3,000,000 lbs. is being removed by coral eating organisms and by currents. Numerous volcanic islands and peaks are found in the Pacific around which reefs develop and island flats are extended. The total population in the Pacific coral reef islands amounts to that of an American city, though it is scattered in about 800 square miles of area.

Wake island is an important Pacific Atoll, and the Great Barrier reef of Australia is a famous Barrier reef. Others are in Indonesian seas. In the east Pacific small colonies occur between Gulf of California and 2° S. Further, in the Indian and the Atlantic oceans, corals are found but not in much abundance; for example, off the coast of Brazil, Antilles and Bermudas in the Atlantic and on the west coast of Indian Ocean and Red Sea.

Tropical coral reefs also record the existence of all the varieties of coral reefs. Apart from barrier, fringing and atolls, shallow lagoon reefs, faros, coral banks, and raised reefs are found. Faros are chains of small atolls with lagoon of moderate depth, forming either a large atoll or a barrier reef. This curious reef is not very common. It is found in Moluccas, on Tagula barrier to the south-east of New Guinea, in Vanua Levu barrier in Fiji and in Maldives.

The Maldives faros include the following: (a) Two circular groups of atolls 260-300 km. long north to south and 90-100 km. wide east to west; (b) Each group contains seven or eight atolls; the lagoon it is between 35-70 m depth and the channel between the atoll is 400 m. deep; (c) Elongated or circular faros about 10 km. wide are found on the edges of large atolls. The lagoon is between 5—20 m. depth. The channel between faros is 25—60 m. deep.

The coral banks are shapeless, shallow lagoon reef. Such are found in Australia and south-east Gilbert islands. The examples of drowned reefs are Carolinas (drowned atoll), Waigeo in the New Guinea (barrier reef). The examples of uplifted reefs are New Georgia in Solomon islands, Mangaia in the Cook islands (all barrier reefs), Poeloe Dana reef west of Timon (atoll) and the Abulat reef in Red Sea (faulted). According to W. M. Davis, Society group of islands stretching for 200 miles, east to west, exhibit all the three types of reef: the fringing in Mehetia, the barrier in Raiatea, and the atoll in other nearby islands.

Again, in true coral seas, two types of islands exist, around which reefs are built: those which are stationary develop cliffed spurs—either

by stationary sea level or due to the lowering of level in Pleistocene time—with a narrow fringing reef developing along it. On the other hand the subsiding island shows a variety of reef development. They do not show cliffs, as the land is subsiding or the shores are already protected by reefs during lowered sea level. The coast line is embayed, and broad barrier reef and atolls are visible.

Marginal Belt Coral Reefs. This area extending between 25°N—30°S represents a belt of coral sea. In this belt the growth of the coral polyps was suspended during the glacial period as the temperature of the sea became much below the requirement. Hence the reefs were exposed and killed. The shores along the lands were cliffed by the intense wave erosion, which is evident by the formation of extensive marine platforms and banks—a characteristic of the marginal belt. Thus the traces of the dead reefs are removed. North-west Hawaiian Islands exhibit one of the best examples of Bank formation—bank atolls or bank barriers. Similar cases are found in the Bahama bank covered with white calcareous mud, lesser Antilles, Bermuda, the Indian Ocean and the south Atlantic. Near Bermuda sounding show two flat topped banks (Challenger and Plantagenet), 10 to 15 miles across, with summits 180 feet below sea level. At the edge the bottom drops 5000 feet.

In other areas where coral polyps were protected during glacial time, the second cycle of development of the reef building starts after the sea level gains its normal level.

A few words about the origin of the marginal coral reefs would make the above points quite clear. The cliffs along the islands here should not be attributed to the stability of the land alone, though in stationary islands of pre-glacial origin cliffs and banks are more marked. In certain instances the occurrence of the embayed shore lines, moderately deep banks, and consequent instability of islands in the coral seas prove the subsidence of islands in this region also. During the course of time they may exhibit coral reefs around their shores with cliffs near the spur ends. The formation of the bank simultaneous with subsidence is explained as the result of erosion by lower glacial sea level.

The subsiding islands of the marginal belt display following features regarding the reef development. (a) Subsidence of land revealed by embayed coasts. (b) Reef growth in pre-glacial time during subsidence. (c) Cessation of reef growth during glacial time, with resulting low level abrasion producing cliffs and platforms. (d) Post-glacial up-growth and revival of reef.

According to W. H. Davis, lesser Antilles displays a regular sequence of forms. St. Kitts shows no subsidence and no wave-cut cliffs. Montserrat has 400—500 feet high cliffs and 2 miles wide platform, but no reefs are found. St. Martin shows submergence and the discontinuous fringing reefs occur near the shore. St. Thomas displays greater submergence, the headlands are truncated by sea cliffs. Redondo is a completely submerged and destroyed barrier reef which was existing in pre-glacial time. The island of Marie Galante, an atoll recently elevated above the sea, represents the initial stage in the second cycle of development.

STRUCTURE OF CORAL REEFS

Every coral reef contains some peculiarity of its own but has a very definite shape. A detailed analysis would reveal certain common features of structure common to all.

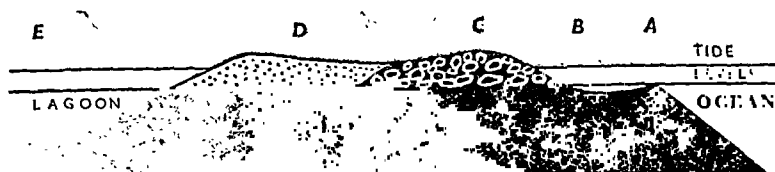


Fig. 38. Section across a coral reef. (After Gardiner). A. Edge of reef, B. Coral flat, C. Boulder zone, D. Sand deposits, E. Lagoon.

Lagoon. It is the first feature developed along the margins of the shore, related to the reef. One of the sides of the lagoon is formed by the island rock, while the other one is made of dead corals. Due to the outward growth of the coral reefs, the sea water is enclosed in between the reef and the land. The declivity of the rock wall is greater in the case of fringing reefs and atolls, where it terminates abruptly in the lagoon floor. In a barrier reef the sides of the lagoon have gentle slope. The bottom of the lagoon is formed by dead corals and is almost flat across the full width. Hence the water in the lagoon is nearly uniform in depth almost everywhere and yet due to local variations, the depth varies between 30—50 fathoms. Further, the width of the lagoon also varies. In a fringing reef a lagoon is almost rare or very narrow, in the barrier reef it is wide with occasional islands in between it, and in atolls the lagoon is quite wide and shallow. The shore of the lagoon is sandy and the reef itself is sometimes concealed. In all these, occasional breaks in the coral reef provide an easy communication between the lagoon and the open sea.

The deposits on the lagoon floor consist of the calcareous sediment derived from the reef wall. The erosion of the dead coral is mostly done by the wave erosion. There are actually none or few living corals in the lagoon. (According to Emery's observation, 2300 coral polyps live in Eniwetok lagoon in Marshall islands). Only some calcareous algae and foraminifera are abundant. Some notable sea cucumbers are also found which chew up the coral rock, and convert the limestone reef into sand and mud. Apart from this, another type of debris is derived from slight erosion of the rock wall of the land, and also due to the excess of deposition of sediment brought by the rivers. This process continuously makes the lagoon shallow. Sometimes irregular coral heads may rise from the floor of the lagoon, wherever they are not covered by the debris.

Thus two activities can be detected, working constantly in a lagoon: (a) the lateral enlargement of the lagoon by destruction of the inner side of the reef wall; (b) continuous steepening of the continental rock wall and flattening of the lagoon.

calcareous algae, foraminifera, sand from the lagoon floor, as well as the blown up sand from the nearby land. The dead corals are continuously broken by the waves. If the reef is wide enough, the higher waves sweep the covers of sand and paleogic deposits across the reef on the other side of the boulder zone along the lagoon coast. If the reef is narrow, coral sand is swept back in the sea or in the lagoon, or deposited in the reef hollows. Hence wider reefs have wide sand mounds as a result of deposition from the lagoon and land side. The whole deposit is easily consolidated by percolating water which dissolves and redeposits the carbonate of lime and thus cements the particles together. This strip of sand attains the height of 10—12 feet above the high tide level and has a gentle fall towards the lagoon. Sometimes due to the action of the waves, seeds are brought from the nearby land, hence vegetation is found here.

(b) *Boulder Zone.* Behind the sand belt a boulder zone is easily distinguished. The debris is rather big in size and quite loose and the material is just the same as in the sand belt. Broken coral boulders are piled up by waves in this portion. The belt varies from 10—30 feet above sea level and is also known as beach conglomerate. The width and nature of this zone depends on the character of the reef. If it is narrow, the boulder zone extends up to the lagoon. Such ridge is absent in Red Sea and Indonesian reefs because of being formed in enclosed seas where powerful wave attacks are absent.

(c) *The Reef.* It is actually in this portion of the coral reef that the true reef is visible. It is deeply fissured, flat only a few inches above the low water level, as open waves usually attack this section. During the low tide the surface is exposed. Hence the corals on the reef flat are often dead. The edge of the reef known as algae ridge is usually raised one foot above the surrounding area and is formed of calcareous algae porolithon rather than of corals. It can live above sea level so long as it is constantly moistened by spray. This feature is absent again from Red Sea and Indonesian reefs due to their formation in enclosed seas.

The section across low wooded islands shows some different features. On both sides of the island the coral heads are visible as shown in Fig. 39. In between the enclosure, sand cay, reef flat, pseudo lagoon, mangrove swamp, dune, high platform, low conglomerate platform rampart (outer shingle ridge) and windward pavement of coral rock are found in succession.

ORIGIN OF CORAL REEFS

Various theories have been put forth about the mode of origin of coral reefs taking into account the fluctuation of the Pleistocene sea level and the stability of the land concerned. The latter fact analyses three conditions: a subsiding island, a stationary island and an emerging land with reefs along them.

Out of the three types of reefs, fringing reef is perhaps easiest to explain. Corals, in past ages, established themselves along the suitable submarine foundation within 30 fathoms of depth. Upward growth, however, ceased when the reef reached the low tide because coral polyps cannot stand a long exposure, but outward growth continued. The material

eroded by waves would hence be deposited on it. But the origin of other two reefs, the barrier and the atoll, is not so easy to explain. There are different views as given below.

SUBSIDENCE THEORY

^{Darwin} This theory was first put forth by Charles Darwin in 1837 and modified in 1842 during his voyage on the 'Beagle', when it became clear to him that coral polyps could only grow in shallow waters. Before Darwin, Chamisso had attempted to relate the origin of reef to subsidence, but it was not fully developed.

The main purpose of this theory is based upon the idea of confinement of coral polyps to a smaller depth. However, in practical observation, their occurrence is found even deeper than the necessary depth. How could these two contradictory elements be united together? It was in order to get a reasoned explanation that the idea of subsiding land form with consequent growing of coral reef has been put forth.

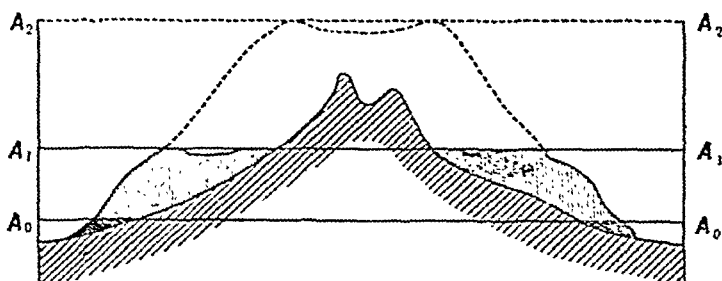


Fig. 40. Formation of Atoll and Barrier reefs by Subsidence. (After C. Darwin.)

A_0 A_0 , sea level of island, with fringing reef in black.

A_1 A_1 , the same after subsidence; island with Barrier reef shaded.

A_2 A_2 , the same after island has been submerged; atoll reef dotted.

Vertical scale much exaggerated.

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Darwin assumes that along suitable platform coral polyps flocked together and grew upward towards a low water level. The resulting reef in this stable condition would be a fringing reef. But as the sea floor and the projecting land in coral seas start submerging, the living corals would find themselves in deeper waters. Hence an urge to grow upward and outward would be balanced by the subsidence of the land. The growth of the corals, as already pointed out, would be vigorous at the outer edge, while near the shore of the land it would be retarded. Accordingly, it would happen that the inner part is flooded by sea water and the lagoon is formed.

Again, the fundamental idea of subsidence, proposed by Darwin, did not imply sudden changes of the level but a gradual sinking, either continuous or by stages. Anyhow, this rate is supposed to be slower than the rate of upward growth of corals.

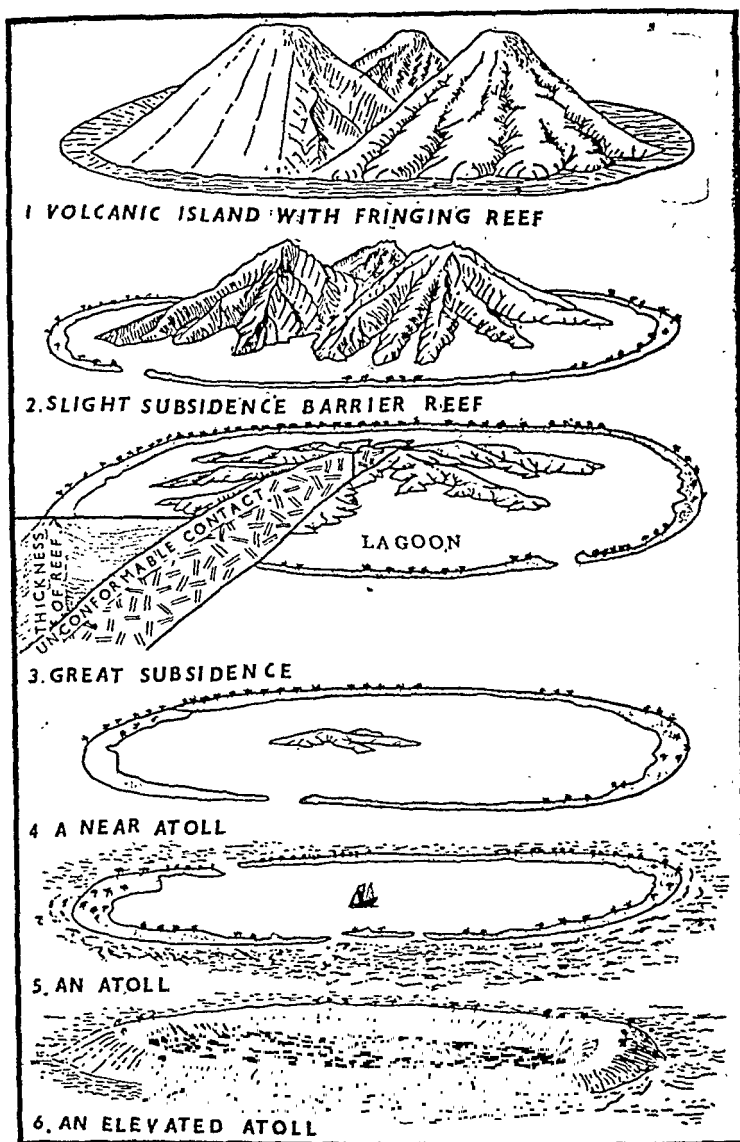


Fig. 41. Stages in reef development on a subsiding island.

(By permission from *Geomorphology* by A. K. Lobeck, Copyright 1939, McGraw-Hill Book Company, Inc; N.Y.)

As a result of this, Darwin postulated that the fringing reefs, barrier reefs and atolls are only three stages in the evolutionary growth of reef. As the land sinks, fringing reef would grow upwards and outwards and help in the formation of a shallow lagoon. Further subsi-

dence would convert it into barrier reef with wide and comparatively deeper lagoon. The width of the reef is also increased due to the deposition of coral debris along it. The last stage of submergence (comparable to thousands of feet) results in partial or complete disappearance of the land and the existence of a coral ring enclosing a lagoon.

Regarding the shallowness of the lagoon, in spite of continued subsidence, Darwin maintains that the depth of the lagoon would be consequently lessened due to the deposition of the sediment from the nearby subsiding land. The coarser material would be directly deposited in the lagoon and finer material and coral debris would be brought by the wave action. Hence the lagoon remained flat and shallow.

The theory, though simple in its presentation, implies that the barrier reef and atoll can occur only in the areas of submergence and the great amount of vertical thickness of coral material, surpassing the depth up to which they should live, is primarily due to the subsidence of land and consequent upward growth of coral polyps.

Evidences in favour of the theory. During "Wilke's expedition", J. H. Dana brought into light that the valleys of the Pacific islands formed by sub-aerial erosion were quite different from the coast line embayments, which were characteristic of a submerging coast line. The coasts of Queensland within the Great Barrier reef and Indonesian seas also revealed drowned valleys and supported the theory of Darwin.¹

The absence of cliffs along the island shores also proves that the land is submerging because cliffs are only visible in a stable area. Moreover, such cliffs, even if they ever existed, are likely to have disappeared through submergence.

Again, the region of the Pacific, which shows signs of elevation in the form of raised beaches, is found devoid of coral reefs, especially barrier and atolls. Only occasional fringing reefs could be seen which could develop even after the emergence of land. On the other hand, real coral seas exhibit no indication of elevations.

Actual observations of submergence have also gone to prove Darwin's theory. Penang and Alexa Banks, north of Fiji islands, is an example of submergence. According to W. H. Davis, Society group of islands stretching 100 miles east to west show a complete sequence in the formation of a coral reef. Mehetia, the first one, is a volcanic cone moderately cliffed. Here no reefs are developed due to accumulation of mud on the shores by erosion. Vigorous reefs form only after submergence, hence Tahiti shows strong cliffing by the sides and the submergence resulting in embayed shorelines with broad and wide reefs along it. Moorea has submerged all the more; therefore the cliffs vanished and the reef is broadened. Raiatea has no cliffed spurs, but deeply embayed shorelines, well developed barrier reef and still greater amount of submergence. Borabora exhibits broader embayments and barrier reef. Maupiti having 10000' subsidence shows a narrow lagoon but broad barrier reef. Finally, there are several small atolls suggesting complete disappearance of the central island.¹

¹ Lobeck, A. K., *Geomorphology*, p. 425.

Apart from the above facts, the observations by U. S. Coast and Geodetic Survey ship 'Pathfinder' (1938) found Palawan Bank, Philippine islands as submerged atolls rising from the shelf covered by 40 fathoms deep water. Dr. Kuenen also found islands of Dutch East Indies related to the submergence.

A fresh evidence is supplied by the pronounced and steep slopes of the rock sides, resembling a mountain summit (mostly in case of atolls). This is attributed to the submergence of the land rather than to sub-aerial erosion which would have resulted in gentler slopes along the extent of the island.

Again, unconformable contacts between the reef and the land mass also prove subsidence. This contact is based on the fact that due to submergence, sub-aerially eroded portions of the land would also subside under the sea level and would consequently be covered by the growth of the coral polyps. Hence there is a sub-aerially eroded land hidden under reef deposition, which is possible only after subsidence. This character according to some proves only the subsidence before the formation of coral reef and not during the time when fringing reef is growing to become a barrier or an atoll. The width of the coral reef and their immense thickness far below the required depth goes against the idea of reefs growing on stable foundations. Only in a subsiding land, corals could grow upward with consequent sinking of the land, and hence increase in its depth.

This fact is verified by boring tests through the coral reef. During 1896 in an expedition of Royal Society headed by Sir Edgeworth David and Solla, many borings in the Pacific atoll of Funafuti recorded the depth of 1114 feet 6 inches and brought forth various layers of once living corals in shallow waters but now pushed downward by subsidence. For the first 750 feet of its length it passed through powdered coral rock, and in 150 feet of the surface coral masses and lithothamnion were found. The rest of the core consisted of compact and crystallized limestone, resulting from compression and transformation of coral rock into dolomite. In this lower layer for 350 feet, the layers of coral alternating with the layers of foraminifera and other organic materials were found. Skeats has brought into light the fact that dolomitization is essentially a shallow water phenomenon. Other bores put down on Great Barrier reef at Michaelmas Cay or Heron island, recorded 400 and 500 feet of loosely coherent coralline material, suggesting a subsidence of at least 60 fathoms. In Bikini Atoll in 1947, it reached 2556 feet depth.

Thus the general evidence is in favour of Darwin's subsidence theory.

Arguments against the theory. The first objection against the concept of subsidence was raised when further detailed observations were made regarding coral reefs. The presence of both fringing and barrier reefs along the same island (i.e. Narai Island, Fiji), was deemed anomalous. To explain this fact, it is assumed that the stability was maintained after a period of sinking and the lagoon was wide enough to permit waves and currents to supply food to the corals of the fringing reef. If slow subsidence is to be accepted, then the difficulty remains. Subsidence, as needed in the theory by Darwin, would imply disappearance of vast land mass in the Pacific, which is not geologically possible.

Murray criticised the borings at Funafuti and said, "The present reef of Funafuti has grown upon a talus of broken fragments, the boring has gone down through that talus and the corals in the core are not in situ but are pieces which have broken off from the edge of the reef and rolled down into deeper water."

Further, contrary to the above, Semper's work in Pelew reefs has shown an area of recent elevation of 400—500 feet, being only 60 miles away from the true atolls. Davis points out that the raised reefs of the island have suffered sub-aerial erosion before corals grew. Later they have subsided to form reef along them. Again, after some time it was uplifted. Nevertheless, Darwin himself agrees in a letter to Semper (Oct. 2, 1879) and to Agassiz (May 5, 1880)¹ that the suitable submarine craters covered by reefs would no doubt resemble an atoll. Hence it is interpreted that atoll could also be found in areas where subsidence had not occurred. Practical observations of atolls rising from comparatively shallower platforms, and not from sunken deep peaks, also proved fatal for this theory.

NON-SUBSIDENCE OR 'STAND STILL' THEORIES

In a few expeditions it was observed that the thickness of corals in elevated reefs amounted only to 200 feet, as in Santa Anna (Solomon islands) and Christmas island (south of Java), whereas Darwin's thickness of coral must amount to 2000 feet. Due to the above facts a new school of thought grew up which was opposed to the concept of subsidence. The non-subsidence theories fall into two groups: those believing that the corals grew upon suitable stable platforms with an unchanging ocean level, and the others suggesting the reef building along the wave cut platform due to the lowering of the sea level. Various scholars under the group have presented quite different views, e.g., Solution lagoon by Murray, Upgrowth on still standing aggraded submarine banks by Rein, outgrowth on rising foundation by Guppy, growth on truncated foundation by Wharton, development on incompletely truncated platform by Tyerman, and growth on sub-aerially submarine eroded platform by Agassiz (Fig. 42).

① Murray. Murray's first observations regarding the corals were in 'Challenger' expedition (1872-76) when he found various submerged volcanic peaks with calcareous deposits in the Pacific. He first presented his theory in 1880 based on stable landform and biological observations. Semper also held quite similar views on the origin of the coral reefs. The first supposition as made by them was an unchanging level of the sea and a stable land form. According to Murray large number of such submarine platforms² and hills were found under the sea forming the base of the reefs. It is not necessary that all these volcanic summits should be of similar height, but they must be near about 30 fathoms deep, so that coral polyps can grow on them.

Hence, he realised that those summits which had risen beyond the coral level had been cut down by the action of the waves and were

¹ Davis, W. M., *The Coral Reef Problem*.

² Boring near Bermuda affords evidence of truncated summits of volcanic cones under the sea.

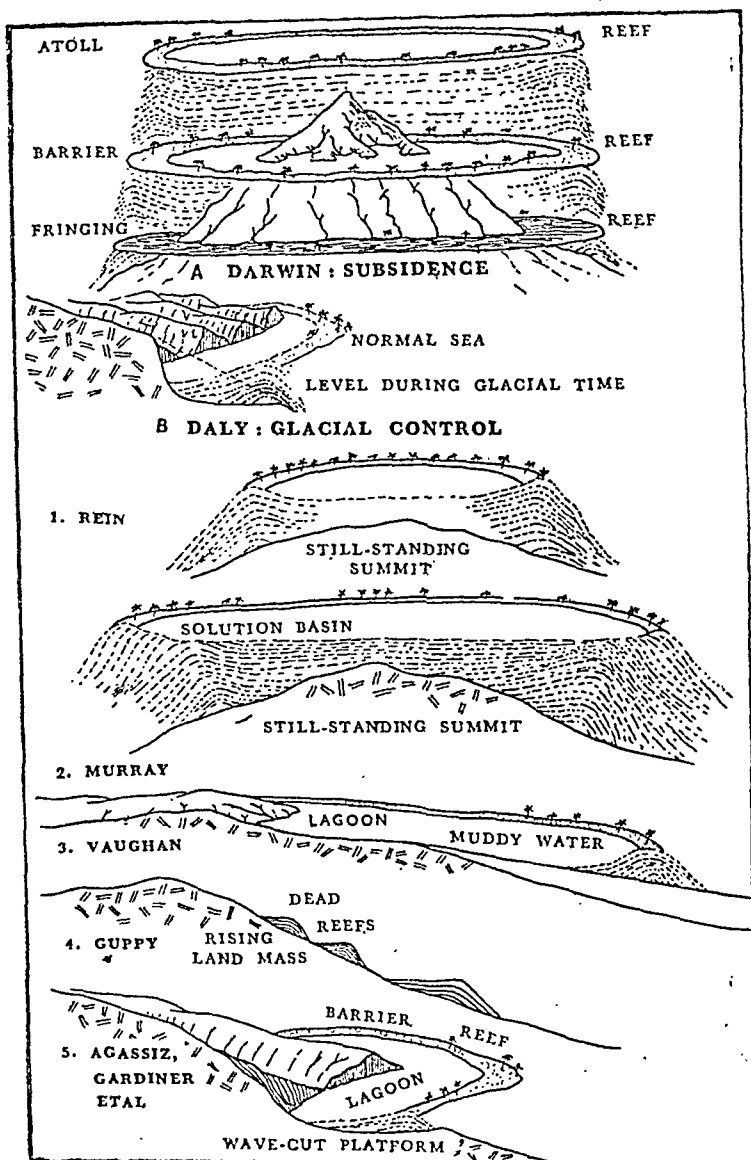


Fig. 42. Theories explaining the origin of coral reefs.
(By permission, from *Geomorphology* by A. K. Lobeck, Copyright 1939, Mc Graw-Hill Book Company, Inc., N. Y.)

dissolved underneath it, e.g. volcanic island with unconsolidated dust can easily be eroded under the sea. Contrary to the above, those peaks which were far below the height sufficient for coral growth had submarine

pelagic deposits laid over them. This deposition is considered to be faster than the rate of deposition in depth because of lesser solution of carbonate of lime. After gaining a suitable foundation at 30 fathoms mainly along the coast, corals would start growing upward in the form of a fringing reef which in course of time would grow outward on the foundation of their own coral debris accumulated at the foot. Thus without any subsidence the reef would be extended deeper into the sea. The barrier reef would result from the continuous outward growth of fringing reef. The conditions of growth are favourable round the edges where the breaking water brings food than in the centre where the water is more stagnant. So, as compared to active growth on the sides, there is delay, starvation, and death in the centre. The lagoon in between the reef and the land is supposed to be hollowed out by the solution of the inner part of the reef where dead corals are easily dissolved. Thus the structure once formed goes on increasing. The outer rim grows outward and the lagoon goes on dissolving and the evolution of a barrier reef takes place from a fringing reef stage even on this stationary island.

Further, the atolls are formed on the top of submarine platforms, growing outward in all directions to form firstly a plantation by corals and later on forming a ring of reef around the solution lagoon in the centre. The corals inside the reef are found dead, but living ones remain growing on the seaward side. Murray has also observed that with the age of the atoll, the ring would automatically grow outwards, and the lagoon would widen and gradually become shallow. Murray's views were supported by Guppy who found in the Solomon islands upraised coral reefs having thin coral bed resting upon calcareous ooze (Pteropod) which had volcanic rock at the base. Further, Dr. Mayer's boring through the fringing reef at Pago-Pago (Samoa) in 1918 at 575 feet shows a volcanic rock underlying the coral at a depth of 121 feet.

Arguments against the theory. Though the theory gained a wide acceptance, yet many objections were raised against it.

In the first place, according to the theory the coral reef building requires the existence of large number of submarine peaks which is not feasible. Again, two contradictory views, i.e. erosion and deposition at the same time over different peaks, are displayed in this theory of Murray, which are difficult to explain. Further, a limit as conceived by Murray cannot be put for the work of erosion or deposition by waves up to the depth of 30 fathoms.

For the lagoon, Murray maintains its existence by solution. It seems unlikely that the lagoons are hollowed in such a manner as according to W. M. Davis sea water has in fact a small dissolving action. If the dissolving action of the sea water is supposed to be sufficient enough to hollow out lagoons, it would also dissolve the pelagic sediment deposited on the submarine peaks. Further, Murray perhaps overlooked the fact of the deposition of sediment into the lagoon. In a stand-still island and lagoon the detritus brought forth by rivers would saturate and fill in the lagoon. This fact is recently observed by Eriwetok who maintains that lagoons are being filled up and not being enlarged.

As the slopes of the atoll descend very steeply at 75° slope on their seaward side to depths of thousands of fathoms, it seems difficult to

conceive how the oozes can rest on a base at such a steep angle. The steepness of the upper part is explained due to being a part of the coral reef, whereas on the contrary the lower part having still steeper slope is only formed of debris.

If Murray's theory is accepted, the depth of the corals should in no case exceed 180 feet, but by observations greater depth of corals is recorded. As regards the depth of the lagoon, which is built on the rock platform 30 fathoms deep, similar depth should be found, whereas 40 fathoms deep lagoons are not rare. Consequently the bottom of the lagoon is made of rock floor, hence solution would occur only along the sides where coral reef is found. In order to get 40 fathoms depth of the lagoon, a solution of 10 fathoms deep rock floor would be required. And for this the theory does not give an appropriate explanation.

⑦ **Gardiner.** Gardiner has attributed the thickness of the coral reef to the work of the deep sea corals (between 40 fathoms to 170 fathoms) flourishing on the eroded platforms. Up to the level of the ordinary corals, deep sea corals and their detritus are deposited, on which reef building polyps thrive upto the sea level (Fig. 43).

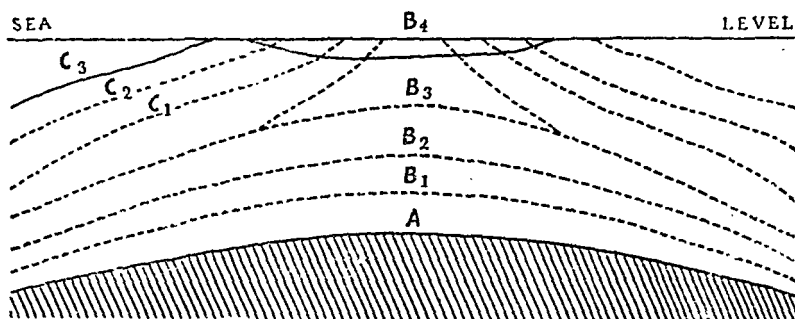


Fig. 43. The formation of an Atoll on an elevation of the sea floor. (After Gardiner).

A. Original mound. B₁—B₄. Building up of same by remains of deep-sea animals, by pelagic deposits, and, lastly, by reef organisms to the sea level. C₁—C₃. Outward extension by accumulation of talus and other materials on the slopes and by further growth of reef organisms, hollowing out of the surface by solution and removal of mud in suspension.

(By permission of the publisher, from *The Unstable Earth* by J. A. Steers. Methuen & Co. Ltd., London.)

Geologists are mostly against the fact that marine erosion can erode a platform up to such a depth. Furthermore, this theory does not explain why there should be an interval between the plantation of the platform and the formation of the reef.

⑧ **Agassiz.** Louis Agassiz, the father of Alexander Agassiz, made a most important investigation in 1851 in Florida reef where a succession of concentric reefs separated by deep channels was found. His other observation was that "one of the most remarkable peculiarities

of the rocks in the reefs of the Tortugas consists in their composition, they are chiefly made up of corallines, limestone algae, and to a small extent only of real corals."

On the basis of his father's work Alexander's expeditions were mainly devoted to the exploration of coral reef problem. While studying Murray's results of "Challenger" expedition he found the following records: "There was enormous number of pelagic calcareous algae, foraminifera in the surface and surface waters everywhere within tropical and subtropical regions, but the dead calcareous shells . . . were not distributed with similar uniformity over the floor of the ocean. . . . The calcareous shells were removed by the solvent action of seawater as they fell towards . . . the bottom of the ocean. The explanation thus given to account for the disappearance of carbonate of lime was then applied to the interpretation of the phenomena of coral atolls." Same results were observed by him in 'Blake' expedition on the coast of Florida.

The theory advocated by Alexander Agassiz is similar to Murray's main idea and emphasizes the formation of submarine platform due to the action of waves around islands and land masses. The depth of such platforms ranges between 30—50 fathoms, on which coral reefs found a suitable base. Hence the thickness of the reef is not much; and they are only thin veneers of corals.

Due to the outward growth of the reef, "the lagoon between barriers and the adjacent shorelines or enclosed by atolls are formed and believed to be scoured out and deepened by wave action. The inside margins of dead reefs of all types are believed to crumble and decay due to solution and boring by marine organisms, the product of such disintegrating processes are washed away by tides and currents."¹

According to John Murray, Agassiz showed the following facts: (i) The barrier or other reefs do not indicate that the shore line has subsided. (ii) The platform under sea is levelled by a variety of ways in different coral regions. Each region has its special condition. (iii) The shallow lagoon is formed by biological, chemical and mechanical activities, continuously in operation even at present time. (iv) The coral atoll in reaching the surface would under special conditions advance seaward on a talus of its own debris. Hence the thickness of the reef seems great. A sounding in Funafuti reef showed that if a boring passed through such a talus, then the coral debris will be found between the actual reef and the tertiary base rocks.

Apart from the above, his expeditions in various tropical waters have never found a single occurrence of the formation of coral reef by subsidence. Hence he totally rejected Darwin's theory of subsidence. This theory faces the problem of explaining the thickness of the corals which should not exceed 180 feet. The action of cliffing and formation of submarine banks as advocated by Agassiz must positively remove all the islands found in between the reef and the shore. Though such cases are found in marginal seas, yet a marked absence of cliffs and existence of islands in the lagoon is found in New Caledonian Reef of Australia.

¹ Worcester, *A Text Book of Geomorphology*, p. 489.

A strong objection to this theory is raised when cliffing along the shore lines is postulated even after its enclosure by a lagoon. As the stagnant water of the lagoon is not as active as the sea waves, cliffing would imply a long period of erosion and hence an interval in which coral reefs would be absent.

(12) **Daly.** Daly is also an advocate of stand-still theory but the central idea of his theory is the changes in the sea level during the Pleistocene period. The theory was put forth in 1915 when he became sure that the coral reefs have been formed since the Pleistocene Ice Age. The traces of glaciation were found on Mauna Kea in 1909 which explained that during the glacial period the surface temperature in this area would have been much less for the growth of corals.

As the result of imprisonment of sea water in the form of ice, the general level of the ocean sank some 33 to 38 fathoms. There was also a lowering of the temperature of the sea, hence the existing reefs were chilled and died. The new sea level was responsible for cut platforms or benches along the continental coasts and islands and for the removal of the traces of islands or dead reefs exposed above 30 fathoms (Fig. 44).

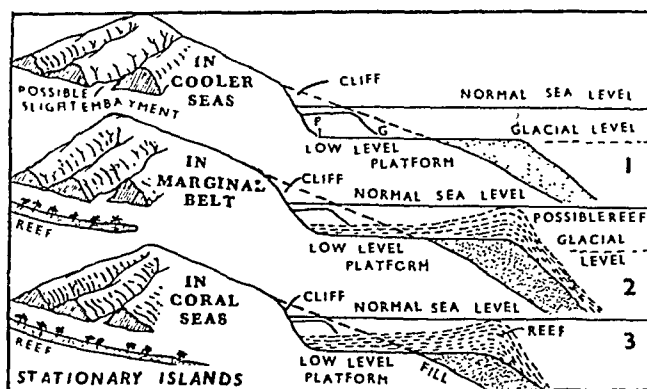


Fig. 44. Effects of glacial fluctuations of sea level on stationary islands.

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When the ice age came to an end and sea regained its normal level, the newly cut benches and platforms were submerged to a depth of 30 fathoms or so. Those corals which were not killed during the glacial time or new coral polyps started to establish themselves on the seaward edge, thus building up fringing reef on narrow eroded platforms and barrier reefs on broad eroded platforms. Atolls would be formed on isolated submarine plateau eroded at the time of lowered sea level. A lagoon of uniform depth would be formed in between the reef and land due to uniform lowering of sea level and comparatively rapid growth of corals on the margins. Daly doubts whether atolls and barrier reefs of today existed before the glacial period though rare atolls can develop locally where

slight subsidence has occurred. The thickness of the coral, under this theory, would also be equal to the lowering of the sea level.

The flatness of the floor of the lagoon and the similar depths of all the lagoons behind the barrier reef and in the middle of the atoll are also explained by the theory. This last fact is also due to the stability of the land, though occasional vertical movements are also taken into account.

The removal of the tertiary sediment, only in the period of Pleistocene age, seems rather difficult. Daly states, "The Glacial control theory emphasizes the Pleistocene as one period of inhibited coral growth, but the bulk of the erosion which has affected the oceanic plateaux is clearly pre-glacial in date."¹ The force of the unhindered wave erosion, as examined by W. M. Davis, is more rapid than the valley deepening and widening by weathering. Hence the erosion of cliffs during glacial period is possible to some extent.

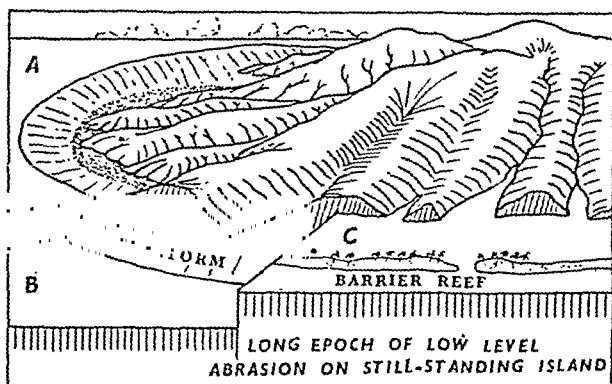


Fig. 45. Effects of glacial lowering of sea level.

Same island with reef at A, emerged by lowering of sea level. At B, followed by the cutting of strong mature cliffs and wide mature valleys. Normal ocean level again at C. Wide embayments with sloping sides; spurs end in plunging cliffs. (After W. M. Davis).

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In the marginal seas the fall of the water level exposed the reefs and hence cliffing process started. But due to lack of vigorous coral growth in this sea, the cliffs are still visible. As compared to the tropical reefs these are in most cases devoid of reefs.

In conclusion we can say that Daly's theory is fundamentally opposed to Darwin's idea though it is not inconsistent with Murray's idea from which it differs in method of formation of platforms.

Arguments against the theory. Leaving aside the slight variations, the depth of lagoons, according to this theory, should be uniform. However,

¹ Steers, J. A., *Unstable Earth*, p. 278.

actual observations by Davis state that even in one single atoll the lagoon depth varies from 120 to 300 ft. In others it varies between 20 and 600 feet.¹ Similarly, the lagoon depths on a drowned atoll or on a submarine bank varied considerably from the normal lowering of the sea level.

Another fact is pointed out by Davis that the unstable areas of the Pacific in relation to the stable areas exhibit no particular divergences of depth. Therefore, it seems that some other cause than the lowered sea level abrasion is responsible for the lagoon depths.

The next argument against Daly's theory is based on the idea of supposed flatness of the lagoon floor, and embayments. At first sight the bottom of lagoon (30 fathoms deep, which Davis thinks is not measured at their most seaward ends) being covered by coral reefs, may appear in favour of Daly's hypothesis. But closer observations reveal that the flatness is only due to the sedimentation on the submarine bench of the shore where no trace of rock is found, while the actual floor of the lagoon remains hidden. Similarly, embayment between the spurs of the land mass may exhibit their rock walls abruptly ending into the sea, while their bottom lay 38 fathoms deep (the stability of the land and lowered sea level would produce 38 fathoms deep bays and embayments also). Investigations have again pointed out that mistakes may occur in measurement due to deposition in the bays because it may also have been shallowed by the excess of sediment brought by rivers. Nevertheless, V-shaped walls with steep slope of the embayments also point towards subsidence.

The occurrence of the shallow banks 200 feet deep and a few miles wide is explained by this theory, but their greater extent like in Macclesfield Bank (55 km wide and 55—60 fathoms deep) remains a problem.

The next important point is the question of cliffing found along the shores. If post-glacial reefs developed after the formation of the cliffs along the land, they should be visible in the lagoons. Side by side, there would probably be no islands along the coast. But, in fact, not only are cliffs of any size not found behind coral reefs, there are often rounded islands dotted about in the lagoon as there are in Great Barrier Reef. Minor cliffing in the lagoon is attributed to the erosion by waves. In marginal seas, cliffs are visible due to lack of vigorous coral growth along the shore while their marked absence from coral seas gives strong reasons for not accepting Daly's theory on all points.

DAVIS' APPLICATION OF PHYSIOGRAPHY TO THE PROBLEM OF CORAL REEFS

Davis started his work on coral reefs between 1914-18, in order to revive and re-establish the old idea of submergence as applied to the coral reef problem. In 1928 he attempted to give concrete physiographic evidences to explain various problems hitherto unsolved.

Davis stressed that the indented and embayed coast lines found in the coral seas no doubt demonstrate the submergence of the land. If

¹ In the eastern part of Fiji island, the depth of lagoon is 90 fathoms, east of Gilolo 101 fathoms and Tizard bank 45 fathoms.

the land would have been stable, cliffs should be visible in lagoons and the depth of the embayment should be 38 fathoms. But as these cases are rare, the evidence proves the validity of submergence.

The bottom of the embayment on observation would reveal great amount of subsidence and deposition. The flatness, according to Davis, is only due to the deposition of the debris but it is not the true bottom of the lagoon. The shallowness of the lagoon may at first seem to go against the subsidence theory. But actually it illustrates the subsidence of the land, consequently depositing the eroded sediment in the lagoon, thus making it shallower.

The disposal of the detritus from the land under standstill theory is not practicable. The sediment would in the meantime fill in the lagoon, and overflowing water would harm the living corals on the other side of the reef. But in subsidence hypothesis any amount of sediment can be easily disposed, as the bottom of the lagoon is subsiding. Again, examples afforded by reefs showing unconformable contacts between reef and the corals also favour the theory of subsidence.

The combination of embayed shorelines and non-cliffed shores in the coral seas is explained with the aid of physiography. In a standstill theory cliffing is inevitable along the shore of the lagoon and embayments would be absent, while on a subsiding island even if cliffs do occur, they would disappear by submergence. Only minor cliffing can be found by wave erosion in the lagoon. Moreover, the embayed coast created by submergence would be visible.

Davis has also taken into consideration the facts of changing sea level. According to him, lowered sea level would create cliffs along the shores and spurs but most of them would be protected by reefs from the wave attack, hence cliffs could not be seen. Further, subsidence would also drown any such cliffs if they are formed.

However, in the marginal belt, Davis points out the action of lowered sea level in forming cliffs because due to an absence of vigorous growing coral polyps the shores were not protected from wave attack and the reef could not have existed there when the cliffs were formed. Thus Davis thinks that glacial changes in sea level can explain abrasion but actually abrasion is not the only fact which could explain the coral reefs fully.

Another evidence in support of the subsidence theory was put forth by Molengraaf and Gardiner that "the weight of a coral mass may cause sinking of its foundation and isostatic readjustments in the substratum to take place." Again, the fact of sufficient uplifts during the period of reef growth which raises reefs in some places to an elevation of 1000 feet above sea level, actually gives support to the subsidence theory. For, if uplift can have been so great, obviously subsidence of similar measure may have occurred.

Thus, the theory advocates the old idea of subsidence but with renewed application of physiography. The theory is also comprehensive in

its application. It includes the changes of the sea level as well as the tectonic changes of the land mass. No other theory can afford such a wide range of probabilities. Davis himself stated: "The main conclusion of my many pages is that Darwin's theory of upgrowing reefs on intermittently subsiding foundations extended by introducing the effects of glacial changes of sea level and temperature as proposed by Daly and by adding such minor modifications as may be called for in special cases will deservedly regain in the present century the general acceptance which is enjoyed through the middle of the past century."¹

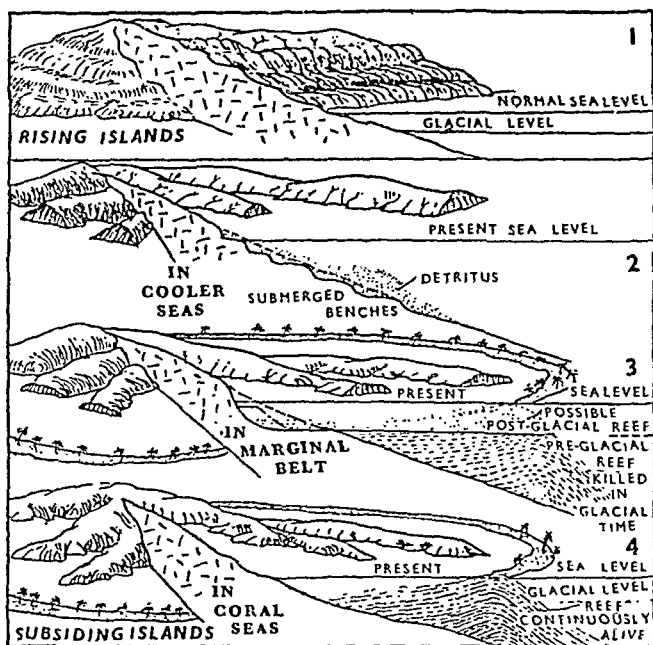


Fig. 46. Effects of glacial fluctuations of sea level on subsiding island.
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McGraw-Hill Book Company Inc., N. Y.).

But in spite of the above evidences, one fact is rather left unexplained in this theory. the assumed equal depth of the lagoons. At this time when further evidences are lacking in this direction, the flat floor of the lagoon and their depths may be attributed to the sedimentation, thus concealing the original bottom of the lagoon which may be of different depths.

Various aspects of coral reefs and numerous theories put forth to explain them have been a continuous problem since the last century. No single theory is all embracing to deal with all possible explanations.

¹ *Geographical Review*, Vol. 25, 1935, p. 160.

Steers has mentioned few points on which future investigators might throw light.

Daly's idea of lowering of sea level during Pleistocene time should take into account the repeated oscillations of sea level so that the reactions of the coral reefs may be explained in relation to raised benches. Davis and Steers believed in erosion of earlier coral structures due to lowered sea level. Kuenen says that the channels in barrier reefs are rarely deeper than 100 m. and this is due to the changing sea level. In the Tertiary period the growth of reef is continuous but after abrupt rising of the sea level in Quarternary period, the growth becomes uneven and rapid. Hence channels are formed. Again, it also explains the common association of barrier and fringing reefs. In Maldives the channels are deeper which are explained by a rapid pre-glacial subsidence.

Secondly, examples of existing inter-relations between different parts regarding the tectonic changes in the land must be brought forth. The fact that a submergence in one part is equivalent to an emergence in the other part should be taken into account.

According to Steers subsidence was found to be dominant in the central and uplift in the western part of the Pacific. As earth movements were active during Tertiary times it is possible that they were extended in the Quarternary times also.

Thirdly, the changes in the climatic belts, during Quarternary glaciation, and their effects on the location of coral reefs, must also be incorporated.

A new idea of the formation of coral reef has been put forth by Dr. Leopold Faustino of the Philippine Bureau of Science,¹ who states that corals do not need a rock foundation. They grow from the loose material of the banks and the circular form taken by the atolls is caused solely by conditions of wave and current. Another idea by Japanese scientists and Steers is that the atolls are the effect of sub-aerial erosion and the forms mainly controlled by limestone solution during the Ice Age (lowered sea level).

¹ Paul A. Smith, 'Submerged Atolls of Palawan', *Geographical Review*, Vol. 25, 1935, p. 160.

Chapter 8 | TEMPERATURE OF THE OCEANS

The study of temperature of the oceans is the subject-matter of Marine Meteorology which deals with that portion of the atmosphere which overspreads the great water masses. The development of this subject began since the time of M. F. Maury of the U. S. Navy who is recognised as the founder of scientific Marine Meteorology.

The temperature of the sea and its accurate measurements has been one of the chief tasks of oceanographers, as it helps in the determination of the movements of large masses of ocean water, their characteristics and the types and distribution of the organisms at various depths.

The temperature of ocean water is recorded by three types of thermometers: thermometers of standard type to measure the surface temperature, the reversing thermometers for sub-surface temperature, and the thermographs. These thermometers are carefully calibrated into centigrade scale showing accuracy even up to 0.01°C . The reading of surface temperature is not a difficult process whereas sub-surface temperature needs special devices of water sampling. The Pettersson-Nansen water bottles having plug valves for their closing and the Ekman bottle having plates seated in rubber to help in closing are the two main types of devices used for the sampling. Here the main difficulty arises in ascertaining the depths of sample water which requires a considerable amount of practical experience. Therefore, the modern oceanographic research makes use of automatic self-recording instruments.

SOURCE OF HEAT AND INSOLATION

Sun is the original source of energy and heat to the earth, in the absence of which the oceans would freeze and the temperature everywhere on the globe would be that of the cosmic space (a degree or two above the absolute zero). Sun is a flaming gaseous mass whose surface temperature is estimated to be $10,300^{\circ}\text{F}$ and in the central part the temperature rises to 50 million degrees F. The diameter of the sun is 1100 times greater than that of the earth and its volume is about 1,000,000 times of the earth.

From such a sun a perennial radiation of its energy is found towards the earth. According to Trewartha,¹ "The radiant energy received from the sun, transmitted in a form analogous to short waves (1/250 to 1/6700 mm. in length) and travelling at the rate of 1,86,000 miles a second is called solar radiation or insolation." Byers defines it as "the rate at which the radiant energy is received on a horizontal surface".

¹ Trewartha, *An Introduction to Climate*, p. 7.

It is estimated that from every square yard of sun's surface the radiated energy is about 100,000 h. p. which can transform earth into a gaseous form within 8 minutes. But all this energy is not received at the surface of the earth, because earth is situated at an average distance of 93,000,000 miles from the sun. Hence only $1/2,000,000,000$ part of the total solar radiation is received at the surface which is sufficient to create all the atmospheric phenomena and amounts to 23,000,000,000 h. p.

The measurement of solar insolation is done by an instrument Pyrheliometer which works on the principle of an indirect measurement based upon temperature effects of radiation falling upon an absorbing element.

The "solar constant" is the solar radiation received at the outer surface of a plane, per minute, on one cm^2 , normal to the incident radiation, at the earth's minimum distance from the sun, i.e. 93 million miles. Thus it comes to about $1.94 \text{ cal/cm}^2/\text{min}$. (Milan Kovitch calculated it to be $2.0 \text{ cal/cm}^2/\text{min}$). During aphelion (when earth is 94.5 million miles from the sun) the solar constant is $1.83 \text{ cal/cm}^2/\text{min}$, and in perihelion (earth at a distance of 91.5 million miles) it is $2.01 \text{ cal/cm}^2/\text{min}$. The mean solar constant is derived on the basis that earth's shape is a sphere, whose area is four times of its cross section. Therefore the values are divided by four and we obtain $0.485 \text{ cal/cm}^2/\text{min}$. as the mean solar constant.

Besides the above fact, the $1/2$ billion fraction of solar insolation is also not wholly received on the surface as greater depletion of solar energy takes place in the atmosphere.

Other minor sources of energy which heat the ocean are the inner heat and the increase of energy by pressure factor. But these sources make minor additions to the total amount of energy and heat received by the earth.

PROCESS OF HEATING

There are various processes of heating the ocean water, i.e. by absorption of radiation from the sun, convection of heat through the ocean bottom from the interior of the earth, transformation of kinetic energy into heat, heating due to chemical processes, convection of sensible heat from the atmosphere, and condensation of water vapour.

Absorption of radiation from the sun. The incoming solar radiation waves are of three types: (A). *Short wave radiation*. These are high temperature radiation waves, which are not visible to human eyes, and pass through the lower part of the atmosphere without being absorbed. The length of the waves is less than 0.4μ [$1 \text{ micron } (\mu) = 0.001 \text{ mm.}$] and it comprises 6% of the total solar energy. (B). *Medium waves*. These are visible light waves between 0.4μ to 0.8μ length and comprise 52% of the solar radiation. (C). *Long waves*. These are low temperature radiation waves and are vastly absorbed by the surface. They comprise 42% of the total solar radiation. Johnson mentions 6%, 49% and 42% values for the above three waves respectively.

As regards solar radiation the atmosphere mostly acts as the green house, i.e. it is transparent to solar radiation but non-transparent to

earth's radiation. Anyhow, apart from the fraction of the solar energy that is received on the surface after being depleted (by absorption and scattering) in the atmosphere, it is again reflected back into the space. This over-all reflectivity is known as the *albedo* of the earth. It is about 42% in general and out of 100 solar radiation only 58% is left to be absorbed or scattered. But according to Moller the reflected energy is 35% (2% reflected from the earth's surface, 6% from atmospheric particles, and 27% from cloud tops). Thus the remaining energy is only absorbed by the land and the sea.

✓ Besides the general nature of the absorption of energy by the surface of the earth, we find greater variations in insolation distribution on the earth due to the angle of the sun's rays, the duration of the day, the latitudes, the depletion of solar energy in the atmosphere and the nature of the land surface.

The earth has a curved surface, hence the angle of sun's rays would be perpendicular at equator and would decrease towards the poles. As same amount of energy at equator would heat up lesser surface as compared to greater surface near poles, the insolation received or the absorption would decrease from equator to poles. Thus there is a latitudinal decrease in the amount of absorption. According to Blair, if 100% energy is received at the equator, then only 88% will be received at 33° latitude, 68% at 50°, 47% at 70°, and 42% at the pole.

TABLE 1
Incoming radiation in latitude zones

Zones of latitudes (in degrees)	Fraction of total area	Shortwave radiation absorbed (cal/cm ² /min.)		
		Annually	Summer	Winter
0—20	0.34	0.39	0.42	0.36
20—40	0.30	0.34	0.42	0.26
40—60	0.22	0.23	0.35	0.12
60—90	0.14	0.13	0.24	0.02

From Table 1¹ it can be noted that latitude becomes the significant factor in determining the amount of insolation received. Besides this, the seasonal changes also affect the angle of the rays at a certain place. Throughout the year the angle of the ray at a fixed latitude does not remain the same, but changes according to the seasonal shifts in the sun's position. The difference is remarkable between 20°—40° and 40°—60° latitudes and is 0.34 and 0.23 cal/cm²/min. respectively. Hence in the month of June, the northern hemisphere receives greater insolation as compared to the southern hemisphere and each latitude receives greater insolation in the month of June than in January. The reverse is the case in the southern hemisphere where January is the warmest month.

¹ Sverre, Petterssen, *Introduction to Meteorology*, 1958, pp. 90-91.

Table 2¹ computed by Kimball shows the average amount of insolation received in gram calories per square centimeter per minute on the sea surface in different latitudes. It shows that with the migration of the sun from the northern to southern hemisphere or *vice versa* the angle of sun's rays changes. The amount of radiation received at sea surface also changes and it decreases towards the poles.

TABLE 2

Latitude	Locality Longitude	Months	
		June	December
60 N	7 E—56 W	·292	0
60 N	135—170 W	·260	0
52 N	10 W	·267	·041
52 N	129 W	·250	·039
42 N	66—70 W	·329	·086
42 N	124 W	·360	·092
30 N	65—77 W	·310	·142
30 N	128—130 E	·238	·135
10 N	61—69 W	·276	·239
10 N	116E—80 W	·239	·219
0 N	7—12 E	·196	·235
0	48W&170 E	·300	·278
10 S	14E; 36-38 W	·206	·320
10 S	72—171 E	·253	·303
30 S	17&116 E	·148	·430
30 S	110 W	·130	·390
42 S	73W; 147 E	·085	·348
52 S	58 W	·039	·302
60 S	45 W	0	·221

Apart from the above, differences in the amount of radiation received at sea surface in same latitudes may be due to several other factors, mainly, the current and cloudiness. This will be discussed later on.

The second factor which affects the amount of insolation is the duration of daylight. This fact is found due to the inclination of the earth's axis. Hence equal hours of day-light are not found at each latitude. Higher we go longer will be the day. At equator it is 12 hours day-light, whereas at 49° latitude it is 16 hours and at 66½° it is 24 hours daylight. The normal deductions would be that greater insolation will be received in the higher latitudes. Though at the outer atmosphere, poles receive greatest insolation in July and January, yet the total insolation is less. At the earth's surface also the actual insolation is however less than that of the equator. For the above facts the main causes are the more slanting rays bringing less energy in greater area, longer summer days are balanced by shorter winter days, and lastly slanting rays passing through greater passage of atmosphere where the energy is depleted.

¹ Sverdrup, *Oceanography for Meteorologists*, p. 52.

The atmospheric passage through which the rays pass to the earth is 5.7 times greater when the angle is 10° and 1.56 times greater when the angle is 40° than the passage (supposed to be 1.0) crossed by 90° rays. Due to greater length of the atmospheric passage, greater depletion of solar energy is found; hence lesser amount is received at the surface. The absorption of radiant energy also varies according to the various features of earth's surface and their physical and chemical composition. Land and water play a major role in the absorption of radiant energy from the sun. Over all the oceans between 70°N and 70°S the average incoming radiation from the sun and the sky which penetrates the sea surface is about $0.22 \text{ gm. cal/cm}^2/\text{min.}$

Thus the major role is played by the effect of the atmosphere. According to Baur and Phillips, out of 100 energy transmitted from the sun, 42 (33 by cloud tops + 9 by scattering) is reflected by water vapour and carbon dioxide, and only 43 (27 direct radiation + 16 by diffuse sky radiation) is received at the surface. Moller states that out of 100 energy of the sun 34 is received directly at the earth, 17 by diffuse sky radiation, 14 is absorbed by atmosphere, 6 is scattered, 27 is reflected by cloud tops and 2 by earth's surface.

This depletion of energy is mainly done by dust and vapour particles and specially by clouds. All these factors combined are known as turbidity factors. Hence turbidity factor is greater in summer, greater in industrial regions, and still greater on oceanic surfaces. Though the general turbidity factor is less in polar regions, yet due to larger passage of atmosphere crossed by slanting rays the great increase in turbidity factor is found.

According to Kimball, if the sky is overcast then only 22% of the total solar energy would be received at the surface, whereas most of it would be reflected back to space by cloud particles. If 52% is clouded, then 42% will be reflected, 15% will be absorbed (11% by water vapour and 4% by carbon dioxide) and 43% will reach the surface of the earth.

The depletion of the solar radiation in the atmosphere is helped by various dust particles, smoke particles, organisms, and water vapour. It is due to three different processes: direct reflection from the surface into the space; diffuse reflection of the radiation waves by particles larger than the wave length (mainly dust and cloud droplets); selective scattering of short waves by particles smaller than the wave length (e.g. scattering of blue colour waves which have very small wave length by very fine dust particles); and the absorption of selected wave lengths, mainly the larger ones, by water vapour, carbon dioxide and ozone. Due to the turbidity factor, which is greater near equator (specially the amount of cloudiness), the insolation received is greatly depleted. Hence out of the total of $0.579 \text{ cal/cm}^2/\text{min.}$ that is received at the outer surface of the atmosphere between $0-10^\circ$ on 21st June, only $0.144 \text{ cal/cm}^2/\text{min.}$ is received at the surface of the earth in the same latitude. Between $30-40^\circ$ latitude there is a similar reduction of energy from the outer atmosphere to the surface of the earth from 0.684 to $0.233 \text{ cal/cm}^2/\text{min.}$ respectively. So another fact comes out that maximum radiation at the surface is not received at the equator due to greater turbidity factor but between $20-30^\circ$ latitude more radiation is received.

Again, the nature of cloudiness also determines the amount of diffused radiation received at the surface. "With a clear sky and a high sun, about 85% of the radiation comes directly from the sun and about 15% from the sky, but with a low sun the proportion from the sky is greater, reaching about 40% of the total with the sun 10 degrees above the horizon."¹ According to Angstrom, the city of Stockholm receives greater diffuse radiation than direct radiation. Again, between 60°—90° latitudes direct radiation is less than diffuse radiation due to the amount of cloudiness.

Thus we find that the atmosphere is the most important factor governing the actual amount of insolation received at the surface. As the nature of the atmosphere varies from place to place, that is, the amount of cloudiness and the nature of reflection changes frequently, hence greater latitudinal and longitudinal differences in the insolation distribution are found. The major difference in the insolation is created by land and sea distribution where the above two factors are found in contrasting capacities.

The absorption of insolation varies on land and sea due to their chemical composition, the method of heating, the nature of the surface, and the reactions produced by them. The land surface receiving equal insolation as the water surface would be heated more as its density is 2.5 times greater than that of water. The solar radiation received on land is penetrated only up to a few feet, whereas over oceanic surfaces the rays penetrate to a depth of hundreds of feet. Thus the same amount of energy is absorbed in smaller area by the land surface, and hence it gets heated easily.

The method of heating for land and water surfaces is also different. The land is heated by conduction and absorption of radiation, whereas the oceans warm up by circulating the heat through convection currents, thus involving greater time. Thus Blair remarked that "Continents are liberal and oceans are conservative".

Let us now study the reactions of these surfaces towards insolation. The land surface mostly absorbs the solar radiation and there is a change in the amount of reflection from the surface of the earth, depending upon the nature and colour of the area. Snow surface and sandy areas reflect much in comparison to the forested area. Over water surfaces variations in the intensity of reflection do not much depend on the nature of the water body which is almost the same from equator to poles, but it varies according to the altitude of the sun's radiation, the sky cover, and the motion of the water bodies. According to Schmidt, if the altitude of the sun above the horizon changes from 90°, 60°, 30°, 20°, 10° to 5° the percentage of reflected radiation out of the total solar radiation would also change from 3, 3, 6, 12, 25 to 40 per cent (on the water surface) respectively.

Another fact that determines the reflection is the cloud cover which in relation to land is more on water surfaces. Hence out of the same amount of energy that is received on the land and the sea, reflection is greater on the sea surfaces and the turbidity factor is greater on sea than on land.

¹ Sverdrup, H. U., *Oceanography for Meteorologists*, p. 51.

On an overcast day, when all the incoming radiation is diffused radiation, the amount of reflection from water surfaces would be 17% according to Schmidt, and 8% according to Powell and Clarke. The above values are mostly true when the sea surface is smooth. If strong waves and currents are found then the percentage of reflection specially at low altitude of sun would be slightly greater. This feature is particularly marked in regions of high latitudes.

Different from land surfaces, ocean bodies are also important as a source of evaporation. Hence most of the solar energy which heats up the land is utilized in the oceans to evaporate water. The result would be lower temperature on the oceans. From the northern to the southern hemisphere or *vice versa*, the amount of radiation received by sea surface changes and decreases towards the poles due to the latitudinal change in the angle of sun's rays. In the month of June when the sun is in the northern hemisphere and the sun's rays are direct in the northern latitudes, the amount of radiation increases towards north pole but decreases towards south pole as we go away from the equator. There is a reversal of this trend in the month of December when the sun's rays are direct in the southern latitudes. Secondly, the difference between the parts of the oceans in the same latitudes is mainly due to difference in cloudiness.

In the total heat received by the sea surface, deduction is also accredited to the effect of reflective tendencies of water surface itself. The strength of reflection of sea water depends on the altitude of the sun, sky cover and the motion of water bodies. For 90°, 60°, 30° and 10° altitude of the sun above the horizon Schmidt has calculated 2.0%, 2.1%, 6.0% and 34.8% respectively of the direct solar radiation and for diffuse radiation from the sky he computed the reflection of 17%.

Convection. According to Geikie, the temperature of the earth increases 1° F for every 64 feet of descent. This results in the increase of temperature in the water close to the bottom of the ocean. The convectional currents due to the internal heat of the earth account for heating of lower layers of water. So, as we come upward, the effect of these convectional currents also becomes less and insignificant. It has been estimated that the heat flow by the convectional currents amounts to between 50° and 80 g. cal/cm².year, that is, 0.95×10^{-3} to 0.152×10^{-3} g. cal/cm².min. This flow is insignificant in comparison to the solar radiant heat received and absorbed by the sea surface. Further, the movement of oceanic water reduces the effect of bottom heat and makes it negligible due to the quick transfer from one region to another. It amounts to one thousandth part of the solar radiation received at the surface. Its role in the heat budget of the ocean is difficult to estimate due to the absence of very accurate thermometers and the effect of pressure of upper layers of oceanic waters in the generation and increase of temperature at the bottom.

Kinetic energy. This energy, in the form of stress on the sea water due to the surface wind and the tidal currents, is capable of raising the temperature of the sea water locally. The contribution of heat due to friction produced by the above two natural forces is very insignificant in the total amount of the heat of oceans. This heat amounts to one-ten thousandth part of the solar radiation. But if the

radiation is about $0.180 \text{ g. cal/cm}^2/\text{min.}$ at a relative humidity of 70 per cent and about $0.163 \text{ g. cal/cm}^2/\text{min.}$ at relative humidity of 100%. Further, it is stated that the diurnal and seasonal variations in the effective back radiation in comparison to the incoming radiation is very insignificant, as the diurnal and annual variations of the sea surface temperature and of the relative humidity are small.

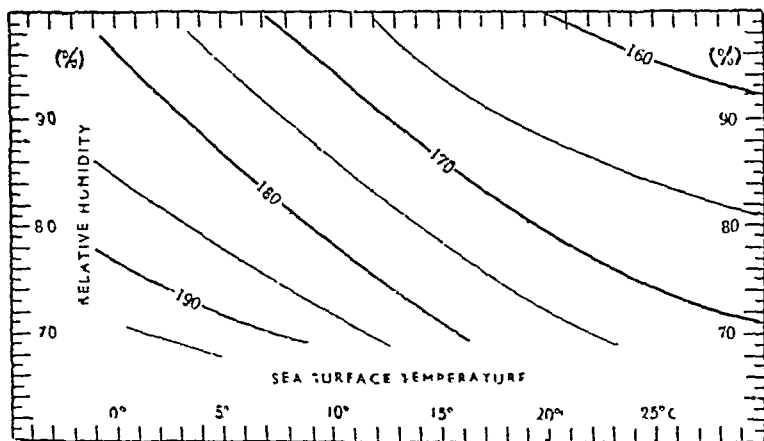


Fig. 47. Effective back-radiation in gram calories per square centimeter per minute from the sea surface to a clear sky is represented as a function of sea surface temperature and relative humidity of the air at a height of a few meters.

(By permission of the publisher, from H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans: Their Physics, Chemistry and General Biology*. (c) 1942. Prentice-Hall, Inc., U. S. A.)

Convection. The exchange of heat between the atmosphere and the sea changes according to the altitude of the atmosphere. The temperature changes rapidly with altitude just near the sea surface and more slowly at greater height from the sea surface. The pre-requisite for heat transfer from the sea to the atmosphere is that the sea surface must be warmer than the air. Thus the air gets heat from the lower layers over which it is lying and makes the stratification of air unstable. Thus the lower warm air moves upward and cold air takes its place. This creates convectional currents and the transfer of heat from the sea to the upper atmospheric layer. The proof of this heat transfer on a large scale can be given by the presence and creation of thunder-storms due to violent atmospheric disturbances. So the turbulence and the eddy conductivity are two essential elements which are responsible for heat transfer from the sea to the atmosphere. In all latitudes the surplus of radiation causes heat-transfer from the ocean to the atmosphere and remains there in the form of sensible heat or latent heat of water vapour. The 'Meteor' observations between 55°S and 20°N show that the air temperatures were lower by 0.8°C than of the water surface temperature. This difference of 0.8°C becomes the cause of heat transfer from the ocean surface to the atmosphere.

Evaporation. Based on the calculations of Angstrom, 90% of the heat received by the oceans is used for evaporation. So the evaporation is of greater importance to the heat balance of the oceans than the convectional transfer of heat. This transformed solar energy contained in the water vapour in a latent or potential form is given out to the atmosphere from the sea surface. When condensation takes place, this latent energy is again released to heat the atmosphere. The transfer of heat in the form of water vapour can be possible when the surface temperatures of the sea are of greater magnitude than the temperature of the air overlying the sea surface because the upward movement of the heat from the sea to the atmosphere requires unstable stratification. On the globe in the middle and higher latitudes due to the greater temperature of sea surface in comparison to the air, the evaporation of water is at its maximum.

Based on observations and their computations the average evaporation from all the oceans amounts to 93 cm. per year but Schmidt, on the basis of the available data of incoming and back radiation, found out 76 cm. per year. Further, in comparison to above figures given by Wust and Schmidt, Mosby has given a revised version which is based on recent measurements of radiation. He calculated the evaporation of the value of 106 cm. per year.

TABLE 3

Average value of Evaporation, E (cm/year) for every fifth Parallel of Latitude between 40°N and 50°S (After Wust).

Latitude	Atlantic Ocean	Indian Ocean	Pacific Ocean	All Oceans
40 N	94	...	94	94
35 N	107	...	106	106
30 N	121	...	116	120
25 N	140	...	127	129
20 N	149	(125)	130	133
15 N	145	(125)	128	130
10 N	132	(125)	123	129
5 N	105	(125)	102	110
0	116	125	116	119
5 S	141	121	131	124
10 S ✓	143	99	131	130
15 S ✓	138	121	125	134
20 S ✓	132	143	121	134
25 S ✓	124	145	116	124
30 S ✓	116	134	110	111
35 S ✓	99	121	97	99
40 S ✓	81	83	81	81
45 S ✓	64	64	64	64
50 S ✓	43	43	43	43

In Table 3¹ Wust has derived average values of evaporation from the different latitudes. According to him the low evaporation in the equatorial regions of all oceans, particularly in the Atlantic and Indian oceans, can be ascribed to the higher relative humidities and the low wind velocities of that area, but in the Pacific the case is slightly modified due to the greater expanse. Further, in the latitudes of trade wind the evaporation is very high particularly in the North Atlantic, the North and South Pacific and the South Indian oceans. The evaporation also varies longitudinally, viz. from the eastern to the western parts of the oceans due to the interaction of ocean current and temperature of the ocean surface.

HEAT BUDGET OF THE OCEANS

The processes so far explained are important in the determination of the heat budget of the oceans. We cannot regard the earth and the atmosphere as separate entities for heat and moisture are continuously exchanged between them. According to the Stefan-Boltzmann Law the emissive power of a body is directly proportional to the fourth power of its absolute temperature. It means that the more the earth is heated up by the sun the greater will be the amount of terrestrial radiation sent out. There is quasi-stationary state, i.e. all the supply in energy is balanced by equally large losses of energy. In general the heat budget of the earth as a whole is given below. A picturisation of all the factors involved in the heat balance has been shown in Fig. 48.

Heat Received	Heat Lost
27 units of direct solar radiation	11 units by radiation through the transparent bands
16 units of sky radiation	120 units by radiation to the atmosphere
107 units of long-wave radiation from the atmosphere	23 units through the latent heat of condensation
4 units of heat transported downward by convection	
154 units	154 units

According to the third equation given below the heat balance is the result of the addition of two equations of warming the ground and warming the air, viz.,

$$(1) \text{ Warming the ground, } G = Ia - R_1 - R_2 + r_d - H - LH + A_o$$

$$(2) \text{ Warming the air } = R_2 - r_d - r_u + H + LH + A_a$$

$$(3) \text{ Warming the ground and air } = Ia - R_1 - r_u + A_o + A_a$$

¹ Sverdrup, H. U., *Oceanography for Meteorologists*, Table No. 10, p. 72.

Here the total incoming radiation I is divided into two: I_a (the part that is absorbed) and I_r (the part reflected either from the earth or from the clouds). R_1 is the long radiation from the ground into the space; R_2 is the long wave radiation which is absorbed either by the clouds or by the water vapour and other gases. Further, r_u and r_d are the radiation emitted upward or downward by the atmosphere; G is the sensible heat to the ground; and H is the sensible heat that flows into the air. LH is the latent heat of water vapour from the ground to the atmosphere. A_a and A_o are the amounts of heat carried horizontally into the column by the winds of the atmosphere and the currents of the oceans.

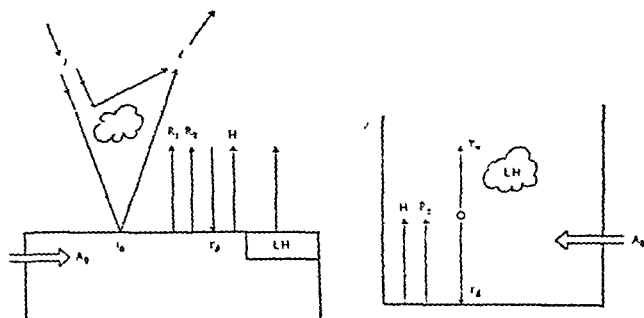


Fig. 48. Illustration of the Heat Balance.

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The heat budget of the atmosphere is controlled by the solar and terrestrial radiation, the heat transport and the latent heat of condensation, whereas the heat balance of oceans is primarily controlled by various processes of heating of the ocean water (absorption of radiation from the sun and the sky, convection of heat through the ocean bottom, the transformation of kinetic energy to heat, sensible heat and condensation of water vapour) and the various processes of cooling of the ocean waters (the back radiation from the sea surface, sensible heat and convection and evaporation and latent heat).

So, for the oceans as a whole the average annual heat budget can be written as:

$$Q_s - Q_b - Q_h - Q_e = 0.$$

Further, if specific regions and time intervals are considered, the complete equation of heat budget of any part of the ocean in a given time interval is:

$$Q_s - Q_b - Q_h - Q_e - Q_v - Q_v = 0^1$$

Where Q_s is the absorption of radiation from the sun and sky, Q_b is the back radiation from the sea, Q_h is the convection of sensible heat to the atmosphere, Q_e is the evaporation and latent heat released by

¹ Sverdrup, H. U., *Oceanography for Meteorologists*, p. 50.

TABLE 4
Heat Budget of the Total Oceans (g. cal/cm²/day)

Latitude	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Direct solar radiation after allowing for cloudiness	202	255	267	233	171	107	30	58	44	39
Diffuse radiation	166	129	106	99	98	95	73	54	41	36
Total Heat Gain	368	384	373	332	269	202	153	112	85	75
Effective back radiation	118	134	144	143	133	116	121	126	131	137
Evaporation Heat	164	170	176	160	125	78	36	13	6	0
Convection	45	45	40	35	20	20	20	20	20	20
Total Heat Loss	327	349	360	338	278	214	159	159	157	157
Gains—Losses	+41	+35	+13	-6	-9	-12	-47	-47	-72	-82

condensation to the atmosphere, Q_v represents the net amount that is brought into or out of the region by currents or process of mixing and Q_r is the amount of heat used locally for changing the temperature of the sea water.

The radiation from the sun and the sky has always been in surplus in all latitudes over the outgoing radiation from the sea surface in the form of long waves. So the effective radiation has the varying degrees of concentration at different latitudes. According to Mosby, the average annual surplus of incoming radiation between latitudes 0° and 10°N is about $0.170 \text{ g. cal./cm}^2/\text{min.}$ and further towards the pole between 60° to 70°N , it is about $0.040 \text{ g. cal./cm}^2/\text{min.}$ Over all ocean surface the average annual of incoming radiation (Q_s) between 70°N and 70°S according to Mosby (1936) amounts (in $\text{g. cal./cm}^2/\text{min.}$) to 0.221 which is equal to outgoing radiation ($Q_b + Q_h + Q_e = 0.09 + 0.013 + 0.118 = 0.221$).

In Table 4¹, Defant has also computed the details of heat budget of the oceans. By taking into consideration all the important processes of incoming and outgoing heat, he has calculated gains and losses for various latitudes, i.e. from equator to 20°N and S there is net gains, then further poleward the amount of losses gradually increases.

According to this nature of heat distribution of the oceans, there is a surplus of incoming radiation through which the oceans exercise a thermostatic control on climate. The water surface reflects a little amount of solar radiation while the major part is absorbed in the sea water and given off to the atmosphere during periods when the air is colder than the sea surface. Further, this surplus radiation from the sun and sky is minimised to zero by the evaporation on the sea surface and the sensitive heat transfer from the sea surface to the atmosphere.

DISTRIBUTION OF TEMPERATURE ON OCEANS

The ocean is a three dimensional body and so the distribution of physical properties like salinity, temperature and density is represented in space by the help of coordinates of latitudes and longitudes with the additional factor of depth. Hence the temperature distribution is completely represented by means of equiscalar surfaces, that is, isothermal surfaces. The temperature and its distribution is determined by the following factors:

(a) The intensity and daily duration of solar radiated energy received.

(b) The depletion of this energy in the atmosphere by reflection, scattering, and absorption.

(c) The Albedo of the surface and its changes according to the angle of rays.

(d) Important physical characteristics of the surface, e.g. if the salinity of the ocean is greater the boiling point is raised and hence the temperature is generally high; similarly, if the density is lower then

¹ Defant, *Physical Oceanography*, p. 93.

the temperature would be higher, and *vice versa*. But a combination of high salinity and high density also produces high temperatures. The nature and the amount of evaporation also determines the temperature.

(e) Heat balance.

(f) Heat transfer through evaporation and condensation.

(g) Importation of warm or cold conditions by the air currents. It is often seen along the coastal regions where the sea water is mainly influenced by the temperatures on the land. Foggy conditions in north-eastern U.S. coast is the proof of the importation of surface winds on the sea. In the middle of the ocean winds also help to equalize the surface temperatures. Besides, winds also help in driving away the warm surface water flowing along the coast, so that in its place an upwelling of cold bottom water is found. Due to this feature, within short distance of the coast very cold and warm waters are found, and, hence the marked longitudinal differences in temperatures are recorded.

This type of upwelling is marked on the western coast of the continent in trade wind belt, and on the eastern coast in the westerly belt. Actually most of the cold currents are found in the regions where upwelling takes place, e.g. Peruvian current, Californian current, Canaries current regions etc.

Due to upwelling of cold water along the continent, we find vast temperature differences from east to west on same latitude. A positive thermal anomaly is created by the flow of westerly wind which carries warm waters along the European coast, whereas in the eastern coast of America cold water upwells and low temperatures are created.

(h) Local weather conditions such as storms, cyclones, hurricanes etc. also influence the sea temperature. Daily variations and seasonal variations of temperature in certain regions are interpreted on the basis of this fact. Under the stress of such winds the ocean surface water is transported in other region, e.g. warm water by Equatorial currents under trade winds and by Gulf Stream under westerlies is transported to other regions. But permanent winds such as trades, westerlies etc. and the wind shifts on the earth do create contrasting conditions in same region.

The movement of the currents is perhaps the most important means of equalising the temperature. But in their effort to do so they transport large amount of water of different qualities into quite contrasting regions. Hence great complications in temperature distribution are produced, e.g. warm currents moving on western coast of high latitudinal continents produce a positive anomaly. Similarly cold currents produce negative anomalies on eastern coasts of mid-latitudinal continents and west coasts of the continents in lower latitudes.

(i) The location of submarine ridge affects surface temperatures. Besides this, the vertical distribution of temperature is also influenced to some extent. This is because of lesser mixing of water on one side of the ridge and comparatively greater mixing up to considerable depth on the other side.

(j) The last factor controlling temperature is the location and shape of the sea. The areas located in lower latitude would have greater insolation and absorption, while oceans having extensive areas in higher latitudes would receive lesser insolation, and the contact with the land areas would easily impose a cooling effect and the mixing of cold polar water would take place. But in the equatorial regions, abundant rainfall brings in a slightly lower temperature. Hence seas along the tropics record high temperature due to clear skies, abundant radiation and marked warming influence of land. Further, the longitudinal extension of seas in lower latitudes is more favourable for high temperatures than latitudinally extensive seas, e.g. Mediterranean shows higher temperature as compared to the Gulf of California.

Similar results could be obtained in different oceans. On the whole Pacific, which is broad in equatorial latitudes and is closed in the north from the Arctic waters, has an average temperature of $66\frac{1}{2}^{\circ}\text{F}$, whereas in the Atlantic the Labrador current and east Greenland current bring ample cold water. Hence the temperature is $62\frac{1}{2}^{\circ}\text{F}$. The Indian Ocean has slightly higher temperature of $62\frac{3}{4}^{\circ}\text{F}$.

As regards the enclosed seas quite different results are found. The seas located in lower latitudes, with no or little mixture from the open sea water, are warmed up by radiation, and conduction heating from the land surfaces. Hence they record high temperatures, e.g. 100°F in Red Sea, 94°F in Persian Gulf etc. On the contrary those bays and partially enclosed seas which have great influx of open ocean water do not record as high temperatures, e.g. the Gulf of Mexico.

In the high latitudes different condition is found. The wholly enclosed seas or partially enclosed seas which do not have much mixing of open ocean water record lower temperatures, e.g. Baltic has 32°F temperature in contrast to 40°F of the open sea. This is due to the fact that the cold land area influences the sea temperature, and side by side comparatively warmer ocean water (due to warm current travelling northwards) does not enter in the enclosed seas. In contrast to this where warm ocean water enters freely, the partially enclosed seas or bays record higher temperatures, e.g. North Sea, Irish Sea etc.

Thus, being influenced and determined by the above controlling factors the temperature changes according to the latitude and the depth of ocean water. Further, it is also marked that there is a seasonal periodic diurnal variation of temperature of the sea which should also be taken into account when discussing temperature distribution.

Diurnal range of sea temperature. The daily march of temperature mainly reflects the balance between incoming solar radiation and outgoing earth radiation. Accordingly, a perfect rise and fall of the daily temperature curve should correspond to the insolation intensity of the day, but in reality it is not the case because there are various processes which are responsible for the daily march of the temperature, i.e. the state of the sky (the daily temperature variations on over-cast days is smaller than on clear days), stability of the air, and the nature of the sea surface etc.

The average range of daily temperature of sea surface in the open sea is generally very small. From observations made in the open sea, the daily range of temperature of water is barely one degree. The time of the highest and the lowest temperatures of the various oceans differs but generally the maximum is attained at 2 p.m. and the minimum at about 5 a.m.

The higher values, particularly in the tropics, were obtained in the daily range of temperature. But these generalizations based on the earlier observations were found to be incorrect and later on it was concluded that the values for daily variations are quite small. "It can be stated that in general the diurnal variation of surface temperature in lower latitudes can be represented by a sine curve with extreme values between 2:30^h and 3^h and between 14:30^h and 15^h, and a range of 0.3° to 0.4°."¹ Further, in higher latitudes the range is still smaller, i.e. only 0.2° to 0.3°. On the data collected by 'Meteor' and 'Challenger' expeditions, it is concluded that the diurnal variation curve is unsymmetrical in the equatorial regions of sea and symmetrical away from these regions.

The range of the diurnal variation of temperature, as observed by Schott in the tropical waters and by Wegemann during the Challenger Expedition, primarily depends upon cloudiness and wind velocity as shown in Table 5².

TABLE 5

Range of Diurnal Variation of Surface Temperature in the tropics

Wind and cloudiness		Temperature range, °C		
		Average	Maximum	Minimum
1. Moderate to fresh breeze				
(a) Sky overcast	...	0.39	0.6	0.0
(b) Sky clear	...	0.71	1.1	0.3
2. Calm or very light breeze				
(a) Sky overcast	...	0.93	1.4	0.6
(b) Sky clear	...	1.59	1.9	1.2

The cloud-free sky helps in greater heating and cooling of sea surface, hence it brings a high range of diurnal temperatures. The calm sky also brings high values as mixing of air is less. The high wind causing thorough mixing at the surface layers does not help in maximum heating and cooling of the surface. Similarly, the overcast sky results in little incoming and outgoing radiation and brings low range of temperature.

The extent of diurnal range depends upon the stratification of the water. The high density of water below will cause less conduction of

¹ Sverdrup, H.U., *Oceanography for Meteorologists*, p. 80.

² *Ibid*, p. 81.

heat and limited range of diurnal variation of temperature. On the 'Meteor' expedition in the tropics at the depths of 50 m. it was found that the range of diurnal variation was reduced to less than 2/10 of the amplitude at the surface.

In the end it may be noted that in the land regions a difference of 20° to 30° in daily temperatures is recorded, but no such daily variations take place in the temperature of sea. So this insignificant variation of diurnal temperature is not important in the physical and biological processes of sea.

Annual variation of temperature. The annual variation of surface temperature is due to many factors, viz., the annual variation of the incoming radiation, the nature of the ocean currents, and the prevailing winds. But the sea is more equable than the air and land in the matter of annual range of temperature. It is heated and cooled slowly, hence the maximum and minimum temperatures of the world are not found on the oceans, and also the oceanic maximum and minimum are slightly delayed, viz. in August and February respectively. The high ranges of temperature as characteristic of land areas (greater than 30°F) are altogether foreign to the ocean water. The difference between the yearly highest and lowest temperatures of the surface of the sea varies on an average by about 10 degrees. But the smaller dependent seas exhibit greater annual ranges of temperature due to the direct influence of the land areas. Thus, in the Mediterranean Sea the range is 20°F and in the Baltic Sea it is about 40°F.

The character of the annual variation of the surface temperature changes from one region to another as shown in Fig. 49. It represents the range curves, that is the difference between the average temperatures in February and August in different oceans. The North Atlantic and the North Pacific have greater range than the southern halves due to difference in the prevailing winds from the land areas and the ocean currents.

In general, the variation in the range of temperature on sea surface depends upon a variety of conditions. The areas of high range are—the lower latitudes, the coastal areas (influenced by land), the enclosed seas and the area under wind shift belts (which have two different types of water masses in a year under the influence of changing winds).

The shape of the sea also affects the range of temperature as comparatively higher range is found in the Atlantic (smaller area) in comparison with the Pacific Ocean (larger area). Similarly, north oceans record higher range than the southern oceans due to free mixing in the latter.

The annual variation in the depths of the water bodies is influenced by (a) variation in the amount of heat that is directly observed at different depths, (b) effect of heat conduction, (c) effect of convectional currents, and (d) variation caused by the lateral displacement of water masses. By taking into consideration the annual variation of temperature at the surface and at the depths of 25, 50 and 100m. in the Monterey Bay, California, Skogsberg has shown the effect of these four factors governing the amplitude of the annual range of temperature according to the depth of the water body. The second example of control

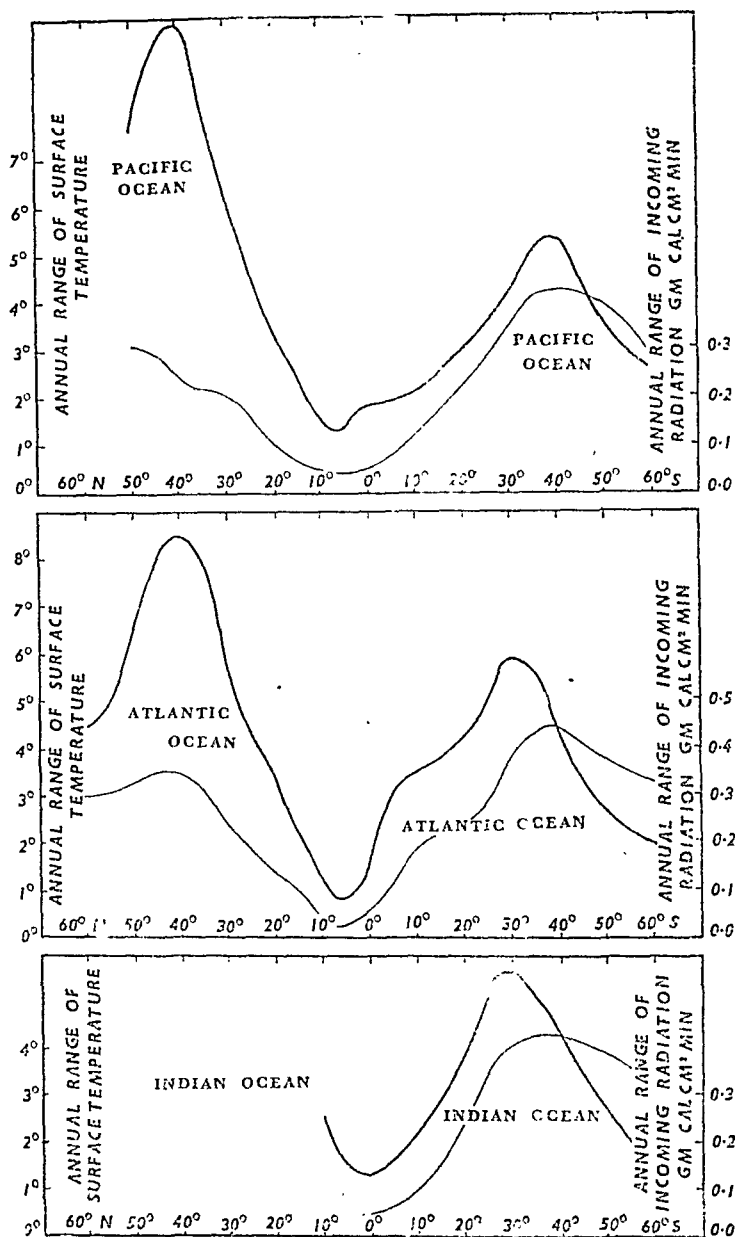


Fig. 49. Average Annual range of surface temperature (heavy curves) and ranges in radiation income (light curve).

(By permission of the publishers, from H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans: Their Physics, Chemistry and General Biology*. (C) 1942. Prentice-Hall, Inc., U. S. A.)

of these factors can be taken from the annual variation of temperature in the Kuroshio off the south coast of Japan. In the Monterey Bay the variations are ascribed to the changes in the conduction of heat of the current and to the seasonal variations of air temperature. And in the Kuroshio current the conduction of heat is the only process which is responsible for the varying range of temperature at depths.

Besides the diurnal and annual variation of the temperature of sea water, there are periodic changes of greater frequency than one year or so, as it has been experienced that the minimum and maximum of sea temperature are not of the same degree from year to year. This long-range periodicity can be ascribed to the change in the intensity of solar radiation. The connection between the two is of a very indirect kind and is to be traced only with great difficulty because the sun is influenced by the eleven years' cycle of sun-spots which slightly affects the radiation amount. Further, the presence of dust and carbon dioxide in the atmosphere is responsible for the reduction of the quantity of heat directly received by the sea. Again, the periodic change known as the precession of the equinoxes, as advocated by Croll and Geikie to explain the occurrence of ice ages, also affects the insolation amount received at the sea surface.

SURFACE TEMPERATURE

The general distribution of temperature of the surface water shows that apart from above controlling factors, the latitude is the most important. The temperature is represented graphically by means of isotherms extending on the oceanic surfaces. The first chart showing isotherms was published by Maury in 1852. A number of features with regard to the surface temperature of the oceans in relation to the latitudes are clearly brought out when we study the data given in Table 6.¹ The temperature decreases with the increasing distance from the equator. The decrease is about $\frac{1}{2}^{\circ}$ per latitude though in actual observation it is slightly different. As a general rule the temperature decreases as the latitude increases but

TABLE 6¹

*Average Surface Temperature of the Oceans between parallels of latitude
(Temperature in degree centigrade)*

North Latitude (in degrees)	Atlantic Ocean	Indian Ocean	Pacific Ocean	South Latitude (in degrees)	Atlantic Ocean	Indian Ocean	Pacific Ocean
70—60	5.60	...	...	70—60	-1.30	-1.50	-1.30
60—50	8.66	..	5.74	60—50	1.76	1.63	5.00
50—40	13.16	...	9.99	50—40	8.68	8.67	11.16
40—30	20.40	...	18.62	40—30	16.90	17.00	16.98
30—20	24.16	26.14	23.38	30—20	21.20	22.53	21.53
20—10	25.81	27.23	26.42	20—10	23.16	25.85	25.11
10—0	26.66	27.88	27.20	10—0	25.18	27.41	26.01

¹ Sverdrup, H. U., *Oceanography for Meteorologists*, p. 75.

in all the oceans the highest values of the surface temperature are found to the north of Equator. This fact is ascribed to the atmospheric circulation and the location of maximum radiation area north of Equator. This thermal Equator according to the seasonal rhythm changes its place very little towards the southern hemisphere.

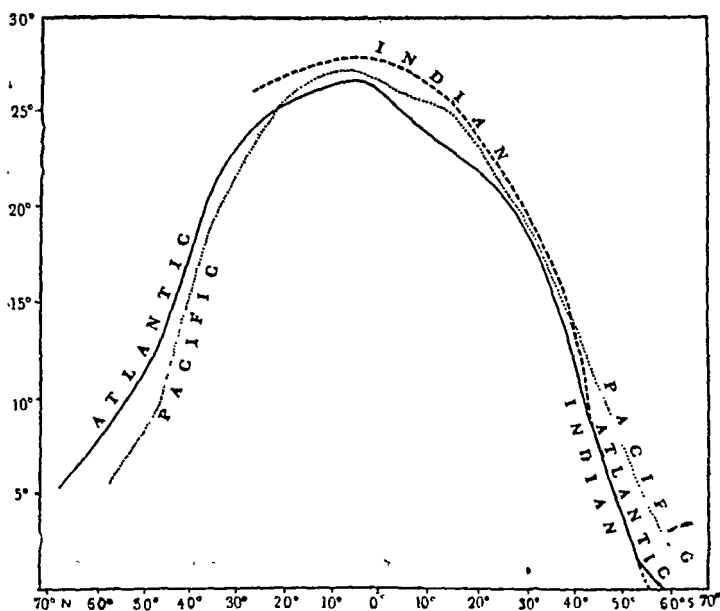


Fig. 50. Average Surface Temperature of the Oceans.

In comparison to the other oceanic bodies the latitudinal decrease of temperature in the North Atlantic is very insignificant due to the presence of Gulf Stream which transports warm water in high latitudes. Thus even in latitudes of 50°-70°N it has a temperature more than 5°C when in other water bodies it is not more than 2°C. The picture of decreasing temperature with the latitudes towards the poles can very well be drawn by seeing the data and the graph line of the South Atlantic. Another feature in connection with the distribution of surface temperature of the sea is the higher temperature in the northern hemisphere than in the southern hemisphere. This is due to the more efficient circulation of water and the transport of heat in the southern hemisphere.

The warmest water as estimated by Krummel is found in 5°N, the coldest between 80°N and the North Pole and between 75° and 80°S. Further, the Pacific among all oceanic bodies has the warmest surface water equal to an average of 19.10°C, whereas the Indian Ocean has 17.03°C, and the Atlantic 16.91°C. This is because of the fact that geographically three-fifth of the Pacific is between 30°N and 30°S. Further details regarding the extremes of surface temperature can be visualised by taking note of the lowest temperature of 3.3°C off New Scotland, the

highest of 32.2°C in the West Pacific and the maximum known variation of temperature amounting to 31.1°C in Japanese waters.

ISOTHERMAL LINES AND TEMPERATURE DISTRIBUTION

Each isotherm is a boundary, delimiting an area where the temperature has a certain mean range of values. They are used in showing mostly the mean temperature. For showing the summer and winter temperature conditions of the sea the months of August and February are the best to represent the contrasting conditions.

Turning to Fig. 51 representing the sea surface isotherms for February, the first thing which strikes the eye is the peculiar way in which the isotherms crowd together in the south of Newfoundland, whereas on the western coast of European continent and in the North Sea they widen out and make northward bulge on the coast of Norway. This fact may be due to the cold water of the Labrador current flowing southward along the American coast which makes the temperature lower than the average temperature for those latitudes, while warm water of Gulf Stream moving towards west coast of Europe makes the temperature higher than the average temperature for those latitudes. So within a short distance from the American coast one meets a change of sea surface temperature from 20°C to 0°C and one has to cross a wide extent of ocean water on the Eastern Atlantic to meet such a great change. Similarly, in the South Atlantic the sea surface isotherms do not stretch due east and west but make an angle with the latitudes. In the western part of the South Atlantic, isotherms bulge towards south-west, but in the eastern part they bulge towards north-west, so the higher temperatures are on the South American coastal waters than on the African coasts. Southward, due to the west wind drift, the isothermal lines observe a sort of parallelism with latitudes. A point of asymmetrical distribution of temperature of the South and the North Atlantic can be noted by the fact that 5°C isotherm reaches the latitude of 70° in the north but it does not go beyond 50th parallel in the south. Further, everywhere on the east and west sides of the Atlantic there is a considerable difference in temperature. 0°C temperature is found off Labrador in between 50° and 60°N and 9° to 13°C on the European side between the same latitudes. In Central Atlantic the isotherms are much distorted due to unstable weather and sea conditions. So these trends of isotherms give us fair evidence in respect of the influence of sea currents on the temperature distribution.

The temperature conditions in the marginal seas vary according to their latitude and location. The seas in the lower latitudes, e.g. Mediterranean, show higher temperature than the neighbouring areas of the Atlantic and the seas in the northern latitudes like epicontinental seas of the Baltic and the Hudson Bay are colder than the adjacent Atlantic.

In the North Pacific Ocean there is a perfect parallelism between isotherms and lines of latitudes, though on the coast of North America the isothermal lines make minor loops towards south due to the warm Kuroshio current and along the Japan coast the crowding of isotherms is intensified due to cold Oyashio current. In the western side of Equatorial part, the isotherms of high temperature due to the south equatorial current make a circular path which separates east and west

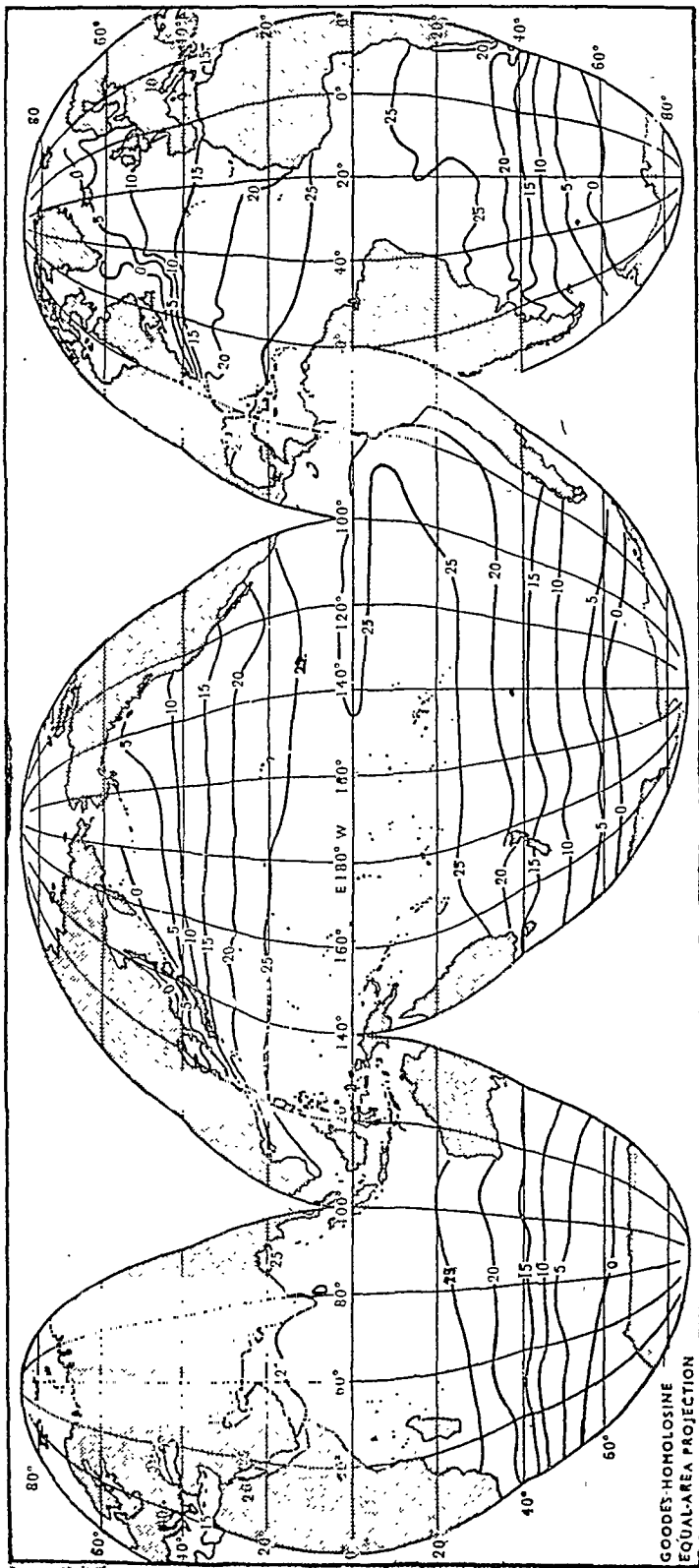


Fig. 51. Surface Temperature of the Oceans in February.

(By permission from *Oceanography for Meteorologists* by H. U. Sverdrup. Copyright 1945. George Allen & Unwin Ltd., London.)

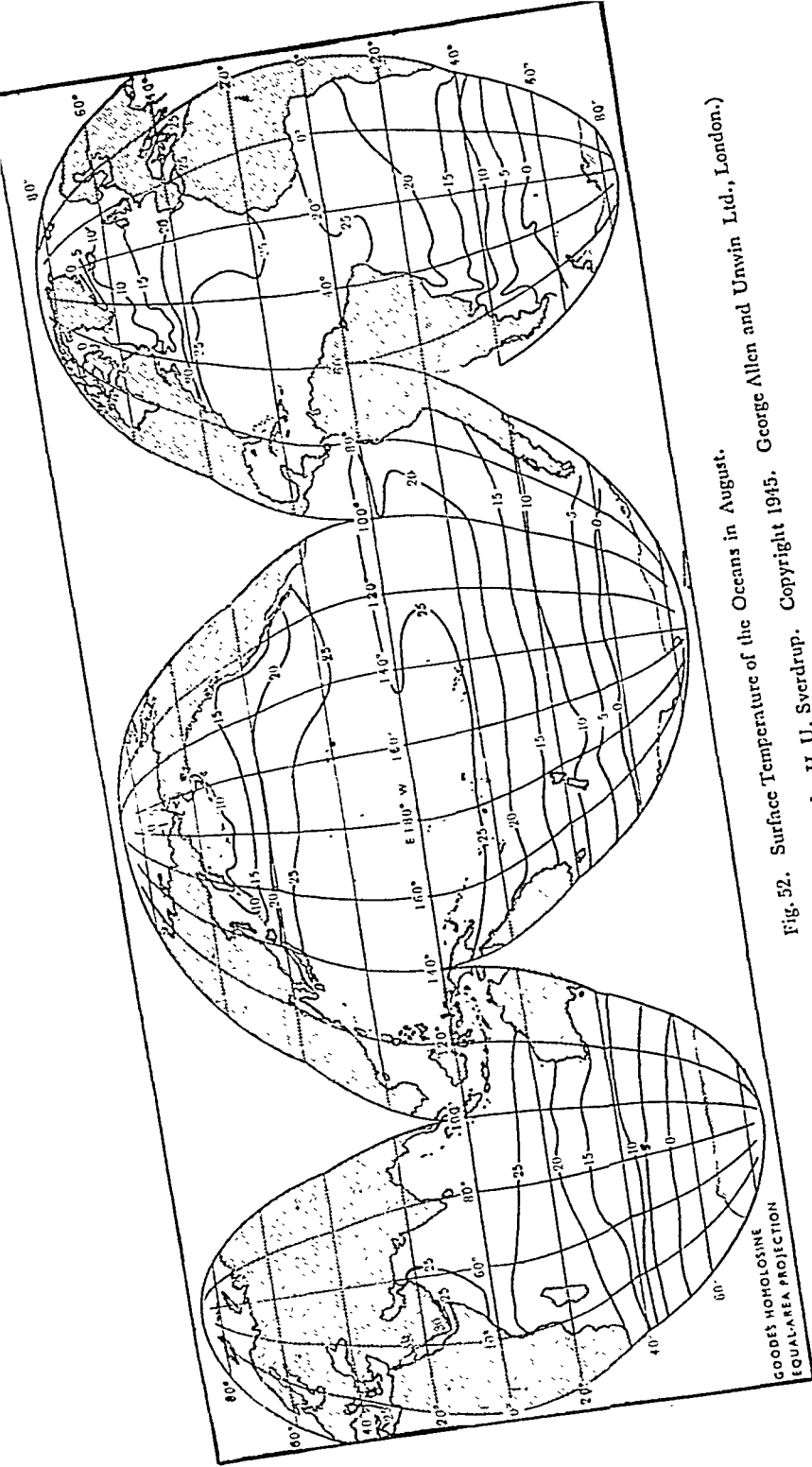


Fig. 52. Surface Temperature of the Oceans in August.
 Copyright 1945. George Allen and Unwin Ltd., London.)

(By permission from *Oceanography for Meteorologists* by H. U. Sverdrup.)

Pacific. In the eastern part a circular region of lower temperature shows the effect of counter-current and the upwelling along west of South America. Further, in the South Pacific, the isotherms have the tendency to run parallel but they move along the west coast of South America due to the cold Humboldt current flowing northwards. The zero degree temperature line runs parallel to the rim of the Antarctica.

In the Indian Ocean the isothermal lines of 25° , 27° and 28° cover the central portion of the ocean. But in the South Indian Ocean, the pattern of isotherms is similar to that of the Pacific, that is, almost parallel to the latitudes, though a loop of isotherms is created at the Cape of Good Hope due to the Agulhas current. On the coast of Africa the isotherms make a bulge southward because a cold current is found setting south westward from Cape Guardaui, the north-east corner of Africa, along the coast which keeps down the sea surface temperature. The same isotherm bends northward in the Arabian Sea, and slightly southward in the Bay of Bengal due to the effect of monsoon drifts. The enclosed sea shows different conditions. South Red Sea has high temperature in the south due to mixture of open ocean water but in the north the cold effect of the land creates low temperature. The temperature in Persian Gulf is lower than the Indian Ocean due to contact with the cold land area.

Fig. 52¹ showing August summer conditions brings out a marked change from that of February in certain parts. The Arctic Sea surface partially becomes free from ice. All the isotherm lines make an upward loop in the Davis Straits where temperature is 5°C . The great upward loops in isotherms formed by the Gulf Stream on the Norwegian coast become insignificant. The isothermal lines in the North Atlantic show a marked northward shift in August. The isotherms of South Atlantic in February and August do not differ so much due to preponderance of water and greater mixing.

In the Pacific, particularly in the southern part, there is a closer approximation to parallelism of the isotherms with the lines of latitudes than in the Atlantic regions. In the west Pacific, there is a large area of sea in the Austral-Asiatic region where temperature rises to over 28°C . This is due to the fact that the westerly flowing equatorial current transfers warm water towards the west Pacific and piles up against the Austral-Asiatic Islands.

As regards the Indian Ocean the highest sea surface temperature of 28°C is recorded in the Arabian Sea and Bay of Bengal area. In the western part of the ocean isotherms become almost parallel to the lines of longitudes with a decreasing tendency towards the African coast. In the southern Indian Ocean the isotherms are parallel to the latitudes. The enclosed seas, e.g. Red Sea and Persian Gulf, attain a maximum of 30°C and 33°C respectively due to the contact with the warm land area. Thus the enclosed seas show contrasting conditions, that is, lesser temperature than the open sea in the month of February and higher temperature in the month of August.

¹ Sverdrup, H. U. *Oceanography for Meteorologists*, Back Chart III—Surface Temp. for August.

From the above analysis of the isothermal maps we can safely conclude that there is a relation between variations in isotherms and the currents of the ocean. Thus under the influence of very strong permanent winds which can bring the surface water in the form of a current, from the regions of higher intensity of solar radiation to the contrasting areas situated in the higher latitudes, heat is carried in different sections of the ocean. Caribbean Sea has slightly higher temperatures than the equatorial region due to piling up of warm water under the stress of trade winds. But the driving away of surface layers (e.g. African coast) also creates an upwelling of cold bottom water resulting in lesser temperature. Thus contrasting temperatures are found in similar latitudes.

TEMPERATURE BENEATH THE SURFACE

Water bodies are generally heterothermal. The temperature decreases according to the increasing depth of the sea, as the sun is the original source of energy. Attempts have been made to estimate the water temperature at various depths ranging from 100 to 3000 and 4000 m. By the analysis of vertical distribution of temperature of sea water, it is calculated that up to the depth of 100 m. the temperatures correspond to the surface temperature, but further lower there is a general lowering of the temperature. It is in this region that the influence of oceanic current is more noticeable in creating warm water in cold layers. Normally 90% of the heat that penetrates the surface of the sea is absorbed in the upper 60 feet of water. The sun's rays have no direct effect below 600 feet and therefore, in spite of movement of water, a vast bulk of sea is relatively cold. In general, the complete stratification may appear in sea as lighter water of high salinity is found above the denser cold bottom water. Probably 80% of water in the oceans has a temperature permanently below 40°F.

The following facts are marked as the characteristics of the vertical distribution of temperature of the sea.

Firstly, in spite of a general decrease of temperature towards the bottom, the rate of fall is not equal at all the depths. Up to 2000 m. the fall is rapid, whereas it is almost stagnant below it. Even in the tropics, the temperature rarely exceeds 40° F at 5,000 feet depth, and below 14,000 feet it decreases from 35°F to 32°F downward. This is due to the action of dense icy water creeping down the ocean floor from the polar regions towards the equator. The following data collected by Murray during the Challenger Expedition shows the mean temperature for all the oceans at various depths.

100 fathoms	...	60·7° F
200 "	...	50·1° F
500 "	...	40·1° F
1000 "	...	36·5° F
1500 "	...	35·3° F
2200 "	...	35·2° F

Secondly, the rate of fall of the temperature is not same at equator and poles, because isothermal surfaces are not parallel to the sea level but on the contrary they make an angle with it. Hence the surface

temperature decreases with the increasing latitudes, whereas the bottom temperature remains almost the same. Thus the rate of fall at equator is greater than at poles. Table 7¹ brings out the fact that there is a latitudinal and vertical decrease of temperature. Similar observations by the German Antarctic Expedition in July 1911 show that at $7\frac{1}{2}^{\circ}$ N at 100 m. the temperature is equal to the surface temperature at 40° N; at 200 m. the same as in 50° N, and 700 to 800 m. it is the same as at 60° N.

TABLE 7

Zone	0— 10°	10— 20°	20— 30°	30— 40°	40— 50°	50— 60°	60— 70°
Temp. °C	26.83	25.60	23.90	20.30	12.94	8.94	4.26
Depth in metres	0	100	200	400	800	1000	—
Temp. °C	26.86	18.57	10.71	7.70	5.13	4.81	—

Thirdly, the surface temperature and its decrease may be found to be influenced by the factor of upwelling of bottom water. In those regions where surface water is carried away, the divergence of water brings lesser temperature on the surface even in lower latitudes. Hence the rate of decrease of temperature becomes less. Similar results are noted in African and Californian coasts etc. In contrast to this the surface temperature is high and the rate of decrease is also high.

Fourthly, the sinking of the dense surface water is due to convergence of dense bottom layer or an intermediate dense and cold layer which spreads in the regions of lower latitudes and affects the rate of fall, e.g. this condition is found due to sinking of cold Arctic and Antarctic currents and also due to mixing in the warm surface current in the higher middle latitudes.

Fifthly, in equatorial region an almost reversal of average conditions is found. At the surface the temperature and salinity is slightly lower due to abundant rainfall but just below it a layer exhibits high temperature and high salinity. Further, at greater depth the usual decrease is found.

Sixthly, there are however certain exceptional areas with higher temperatures even at greater depth, e.g. the Saragasso Sea, the Red Sea, the Sulu Sea and the Mediterranean Sea etc. In Saragasso Sea, the higher temperature even at the bottom is due to higher insolation, anti-cyclonic circulation of currents around it and lesser mixing of the cold waters. In the case of enclosed seas, higher temperature is still found at the bottom because of their basin like form, free mixing checked by the shallow sea situated on submarine ridge. Hence, in Red Sea the bottom temperature at 1000 fathoms is 70° F in contrast to 38° F in the

¹ Jenkins, J. T., *A Text Book of Oceanography*, p. 52.

Indian Ocean. The decrease of temperature here is only 10°F in 1000 fathoms. In the Mediterranean Sea, the decrease of temperature is from 56°F to 54.5°F within 1200 m. whereas the Atlantic Ocean records 30°F temperature at 1200 m. depth.

Again, in the enclosed seas of higher latitudes different observations are made. At the surface the temperature is low due to abundant fresh water, while denser water of slightly higher temperature and high salinity which moves in as a sub-surface current from outer ocean remains at the bottom. Hence a reversal of temperature conditions is found.

Lastly, due to the existence of submarine barrier which holds back the open ocean circulation to enter the enclosed seas lesser mixture of water is found. Hence on different sides of the submarine barrier the temperature conditions are not same.

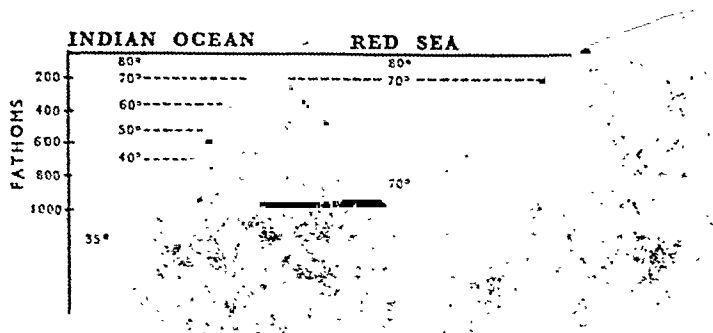


Fig. 53. Showing Red Sea Barrier.

In Fig. 53 the effect of barrier in the temperature variations according to the depth of bodies has been shown. The submarine barrier rising up to 1200 feet from the bottom at the Strait of Bab el-Mandeb acts as a barrier. Hence the surface temperature in the Red Sea is 85°F , whereas at the depth of 800 fathoms it is 70°F for the hottest month; on the other side of the ridge in the Indian Ocean the temperature is 37°F at 800 fathoms. If the barrier is removed, the bottom temperatures in the Red Sea and the Indian Ocean would correspond to each other. Similar example is found at the Wyville Thompson ridge (between Scotland and Faroe island) which is about 600 m. deep and separates the cold Arctic water from being mixed with the warm Atlantic water. Hence at 1000 m. on the Arctic side and on the Atlantic side the temperature is 30°F and 47°F respectively.

Thus we see that the variations of the temperature with depth of the water are controlled by several factors like the surface and sub-surface currents, the density current, the effectiveness of incoming solar radiation and the nature of the surrounding land areas and submarine relief.

ISANOMALOUS TEMPERATURE OF SEA WATER

The difference between the mean temperature of a place and the mean temperature of its parallel is called the thermal anomaly. This

difference is because the mean temperature of the parallel only takes up the radiation feelings whereas the mean temperature of the place is calculated on the basis of various terrestrial controls which affect the climate. The thermal anomalies are mostly found in the northern hemisphere. In the month of January the positive thermal anomaly in the North Atlantic Ocean varies from $+4^{\circ}$ to $+20^{\circ}$ and in the western North Pacific from $+4^{\circ}$ to $+18^{\circ}$. But the Indian Ocean, the Southern Pacific and the South Atlantic oceans record 0° anomaly or even negative anomaly values. In the summer months the situation is reversed and the oceans have anomalies in negative, the greatest being in the eastern Pacific off the coast of Canada and U. S. A., recording up to -8° . The anomaly of -4° is found off the coast of Peru and north-east Canada.

ICE IN THE SEA

The study of the temperature of the oceans would be incomplete without the study of the sea ice and its impact on the equatorial or temperate waters. In the neighbourhood of the poles, the temperature of the surrounding area is so low throughout the year that ice forms a permanent feature on the sea surface. The ice is increased due to three sources: rivers, precipitation and freezing. In the Arctic Ocean, river-ice plays an important part on the Siberian and American shelves, but no such ice is found in the Antarctica.) The second source is due to the snow fall over the land in this region which accumulates year after year to form the field ice. When this ice is disturbed by the wind, it becomes uneven consisting of broken pieces of ice and hence *Floe-ice* is the name given to it. Pack-ice is formed from broken up floes, while Pancake ice is a newly frozen ice of sufficient thickness. The third means of ice formation is by freezing of water. The freezing temperature of the sea water is not 0°C but an appreciably lower temperature depending on salinity, that is, lower the salinity higher is the freezing point and *vice-versa*. On an average sea water has 35 salinity and the freezing point is $3\frac{1}{2}^{\circ}$ below the freezing point of pure water.

The process of ice formation continuously separates the crystals of brine and pure water. Only in rapid freezing, the saline crystals are also trapped. Thus slowly formed sea ice is less saline than the rapidly formed ice. The ice formed from sea water is heavier than the pure water ice. It is also observed that older the ice, less saline it becomes.

The rate of growth of the sea ice in thickness is also calculated. If the temperature is 5° below freezing point, in 100 days 71 centimetres thick ice would form. If the temperature is 20° below, the thickness of ice after 100 days will be 142 centimetres, and after 200 days it will be 201 centimetres. Accurate observations of the rate of growth of ice have been made by Drygalski. "At first the growth is very rapid—from the 2nd to the 20th December 25.4 cms; from the 20th December to the 19th February 56.4 cms; to the 22nd March 73 cms; then to the end of May 72 cms; after which in June it rapidly commenced to melt."¹ Generally it is seen that the ice gradually increases in thickness until the middle of winter. After this, there is a little increase, for evaporation

¹ Jenkins, J. T., *A Text Book of Oceanography*, p. 84.

acts above the surface and melting below. Hence it does not remain in a uniform sheet but exhibits a hummocky surface.

Distribution of sea ice. In the northern hemisphere, the Arctic Ocean is a source of great pack ice, which varies in thickness from 2 to 14 feet and extends up to 60°N along the Greenland coast. The maximum extension is found during May and minimum in August. In the month of May, most of the northern shelf of continents is covered with pack ice, the only exception being the whole coast of Norway, round North Cape to Cape Sviatoj. The sea between Spitsbergen and Greenland is usually covered with pack-ice throughout the year. The spread of ice is here subject to the movement of wind wave and drift, which carries ice into otherwise ice-free seas. The most marked disintegration of ice starts in June and July, though this is not definite and differs according to the climatic changes of the atmosphere.

In the southern hemisphere, a permanent ice cap is found which surrounds the land and blocks the movement of the ships. This is actually land ice and not sea-ice. In the Arctic, the sea is blocked by land, hence the ice is sea-ice and shows changes according to the season whereas in Antarctica ice extends on all sides into various oceans due to the absence of land barriers.

Icebergs. Large masses of ice, which have been split up from their sources and float on the sea surface, are known as icebergs. On freezing the ice expands and becomes lighter than water of equal volume. Ice has density of 0.9 and sea water has 1.025. Hence it floats with 9/10 part below the sea level. According to Steenstrup, the portion above and below the water has 1:7.4 to 1:8.2 ratio. The tabular ice has 1/7—1/9 part above water. Krummel gives 1:8 as an extreme case and 1:4 as the maximum case while average is between 1:5 to 1:6.

Icebergs are of numerous sizes. They vary in extent from a few yards to many miles in length and breadth. Their height above sea level also ranges from a few feet to 1700 feet. In southern hemisphere the size of the icebergs is greater than in the northern hemisphere. Icebergs float in the regions of their origin but usually drift and currents bring them down into lower latitudes to play a hazard in navigation. The direction of the icebergs is influenced by the direction of the wind and the deflection by the earth rotation, as noticed by Nansen in the Arctic waters. Their speed is usually in relation to the speed of the wind. If the latter is flowing at the speed of 30 knots, the iceberg would move at the rate of 4 nautical miles per day. Sometimes icebergs are found moving in opposite direction of the wind, under the influence of the powerful sub-surface water mass.

Rink noted that the Arctic icebergs mostly originate on the west coast of Greenland, through the fiords, namely, Jakobshavn, Torsukatak, Karajak, Kangerlugsuak, Umanak, and Upernavik, extending from south to north between $67\frac{1}{2}^{\circ}$ to 73°N . These icebergs originate in the form of ice sheet over Greenland and move up to sea as valley glaciers. The breaking up of the glacier in the form of an iceberg is known *calving*. This process is active both in summers and in winters but only during summers they get outlet to float into the sea as a result of breaking up of the fiord mouth. Each year, approximately 10-15 thousand icebergs originating at Greenland coast float into the Atlantic Ocean through the

Baffin Bay. About 700 or 800 icebergs at one time were observed by Admiral Markham. In the James Bay two types of currents are found, that is, one moving northward along the western coast of Greenland and the other southward along (Labrador current) American coast. The former branch flows into the James Bay carrying icebergs during spring and summer (April to June), whereas the latter brings icebergs down nearly up to 40° N. From the Greenland coast to the Grand Banks is a distance of 1800 miles which is covered by an iceberg in one year.

During their southern voyage most of the icebergs disintegrate and only few reach up to south of Newfoundland. At some time they are observed in the vicinity of Sable Island, south of Nova Scotia, where due to melting of the ice, comparatively lower temperatures are found. The southern and eastern limits of ice in the western North Atlantic vary from year to year and month to month. In the early months of the year the whole portion of the Grand Bank is covered with icebergs. Due to the movement of Labrador current, east and north-east over Flemish ridge (east of Grand Bank) icebergs drift up to 40° W. Some are found in 51° N- 11° W, 51° N- 19° W etc.

On the east coast of Greenland icebergs, though rare, turn eastward from Novaya Zemlya to Spitzbergen in the current along east Greenland and turn round Cape Farewell through Denmark Straits and thus enter Davis Bay and get into Labrador currents. Off the Norwegian coast, Siberian coast, or in North Pacific, icebergs are never found due to different reasons. The Norwegian coast has warm effect of Gulf Stream throughout the year while there is no nursery for icebergs in the North Pacific. The water of the Bering strait is too shallow to let them pass into the open sea. Moreover, the climate also does not favour iceberg formation.

In the southern hemisphere the icebergs of Antarctica are much bigger in size than those of the Arctic and have longer life. The Arctic icebergs remain for two years, whereas Antarctica icebergs remain for about 10 years. This difference is due to greater mass of icebergs and lower temperature of the surrounding sea. Therefore melting does not take place so easily. These icebergs originate as ice caps on Antarctica continents at irregular intervals. According to Russel these icebergs get free by the action of the Antarctica continent volcanoes which erupt and shake the coastal ice. Thus icebergs are broken off from the ice cap and are set adrift to float.

The average height of the iceberg is 800 feet above sea level and sometimes so large that they are named ice islands. Between 1891-1916 six records of Antarctica icebergs showed their length to be 50 miles, the largest being between 70 and 82 miles.

These icebergs are carried northward by Falkland, Benguela, and South Australian currents up to 40° S in the Atlantic and 50° S in the Pacific. In north-east of Falkland these icebergs are most dangerous. In general, northern boundary of icebergs around Antarctic is supposed to be 45° S. Icebergs are absent south of Australia, east of New Zealand and between Falkland island and South America.

NATURAL REGIONS OF THE OCEANS

After studying the temperature of the ocean, its interactions and resultant features, one is led to the idea of natural regions of the ocean. The consideration of regional areas in the sea came from the past (such as Doldrum and Sargasso) and suggests the scope for such presentation.

Schott has attempted to classify the regions of the ocean on the basis of all the variable factors found in the upper layer of the sea. One criticism goes against his classification that he attempted to separate the divisions on the basis of differences rather than on the basis of similarities. The following is the list of regions found in oceans as given by Schott.

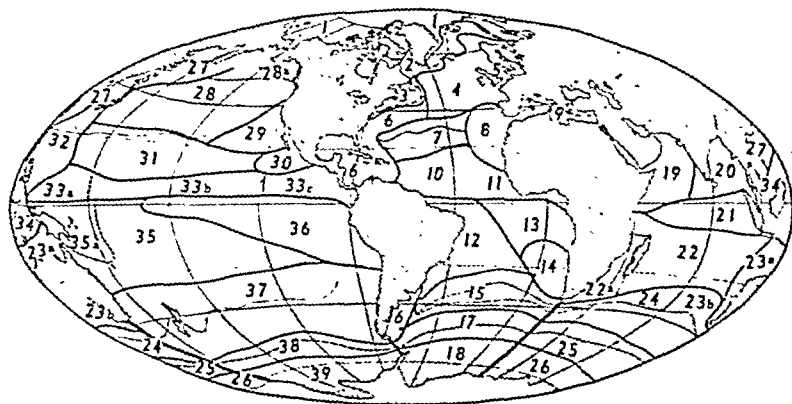


Fig. 54. Regions of the Oceans.

(By permission from, *The Geographical Review*, N.Y.)

Atlantic Ocean

1. North Polar Sea.
2. North Atlantic Sub-polar region.
3. North west Atlantic Marginal Sea.
4. North east Atlantic Drift region.
5. North Sea and Baltic Sea.
6. Gulf Stream region.
7. Sargasso Sea.
8. Morocco region.
9. Mediterranean and Black Sea.
10. North Atlantic trade wind region.
11. Atlantic Equatorial region.
12. Brazilian region.
13. Ascension region.
14. S. W. African region.
15. South Atlantic Middle latitude region.
16. Patagonian region.

17. South Atlantic Sub-polar region.
18. Atlantic South polar region.

Indian Ocean.

19. Arabian Sea including Red Sea and Persian Gulf.
20. Bay of Bengal.
21. Indian Equatorial region.
22. Mauritius region and Mozambique region.
23. (a) North-west (b) South-west Australian region.
24. South Indian Middle latitude region.
25. Indian Sub-polar region.
26. Indian South polar region.

Pacific Ocean.

27. East Asiatic Marginal seas.
28. North Pacific, Mid-latitude including Alaska region.
29. Californian region.
30. Mexican region.
31. North Pacific trade wind region.
32. Japanese region.
33. Pacific Equatorial region.
34. Malayan region (Sunda seas).
35. South Pacific Island clusters.
36. Galapagos region.
37. South Pacific Middle latitude.
38. South Pacific Sub-polar region.
39. South Pacific South polar region.

Chapter 9 | SALINITY

Among various physical properties of the ocean, salinity is perhaps the most important variable besides temperature and pressure. Commonly defined, it is the ratio between the weight of the dissolved material and the weight of the sample of sea water. Oceanographers define salinity as "the total amount of solid material in grams contained in one kilogram of sea water, when all the carbonate has been converted into oxide, the bromine and iodine replaced by chlorine and all organic matter completely oxidized" (International Commission, 1902).

It plays a significant part in the composition of sea water. Its variations between 34 and $37\frac{1}{2}$ per mille determine other physical properties of sea water such as compressibility (depending on salinity and temperature which produces density differences), thermal expansion, refractive index and the temperature of maximum density. The freezing point of sea water is also dependent on the amount of salts found in it since solid bodies such as salts have a very low vapour tension. It means that the temperature of sea water must fall below the freezing point of the dissolving substance before it begins to freeze. Consequently, the freezing point of sea water varies with the amount of dissolved salt—the greater the amount of salt, the lower the freezing point. For example, the North Sea, which has comparatively greater salinity, remains open throughout the winter. Similarly, the boiling point of sea water is higher than that of fresh water.

Again, salinity introduces altogether new properties like osmotic pressure (pressure depending on the temperature and the chlorinity of water) and electric conductivity in the ocean waters. The former varies with the increase of density—Baltic sea having 7.5% salinity at 18°C temperature has an osmotic pressure of 4.9 atmospheres while the Red Sea of 40% at 30°C has osmotic pressure of 26.7 atmospheres. Further, it is noted that the degree of evaporation is also affected by salinity, i.e. higher the salinity, the lower will be the evaporation and therefore lesser humidity. It increases scattering of radiation resulting in greater absorption in layers of higher salinity. The structure of the ocean, the movement of the water, and above all, the distribution of fish, sea animals and plankton all are determined according to the amount of salinity of sea water.

COMPOSITION OF SEA WATER

Sea water is almost a universal solvent and therefore it is a complex solution of many mineral substances found in dilute form. It is assumed that the sea water was in the beginning only faintly saline

and its saltness has been increasing ever since. As a result, the total 329 million cubic miles of sea water contains on an average about $34\frac{3}{4}$ tons of salt per 1000 tons. Joly estimated that 50,000 million tons¹ of salt is still found in the sea which if dried will cover the entire globe with a layer of 150 feet thickness and the land area with a layer of nearly 500 feet thickness. It is further estimated that if the salt from the ocean is withdrawn, the sea level would fall 100 feet below the present level.

Various methods have been used to determine the amount of salt in the sea. The titration method is based on the constancy of composition of the dissolved matter; the hydrometer method determines the density of the sample of sea water by which salinity is calculated; and the last method is by measuring the electric conductivity or refractive index of the sea water at a known temperature.

Chemical analysis by Dittmar during his 'Challenger' expedition in 1884 reveals the existence of 47 different sea salts. In this solution, common salt (sodium chloride) is by far the most important constituent, though various other ingredients are also found in small but significant amounts. These are so-called nutrient salts (mainly phosphates, nitrates and nitrites) which are used by plants primarily and animals secondarily in their metabolism and growth. Among all the salts in the sea, seven are the most important. The list of salts and their weight and percentage as given by Dittmar is given in Table 1.

TABLE 1

Salts	Amount‰	Percentage
Sodium Chloride	... 27.213	77.8
Magnesium Chloride	... 3.807	10.9
Magnesium Sulphate	... 1.658	4.7
Calcium Sulphate	... 1.260	3.6
Potassium Sulphate	... 0.863	2.5
Calcium Carbonate	... 0.123	0.3
Magnesium Bromide	... 0.076	0.2
	35.000	100.0

According to both Forchhammer and Dittmar, the relation in which these salts are found is constant in the ocean everywhere, that is, the proportion of different salts remains unaltered. Only the total amount of salt in 1000 grams of sea water varies generally from 33‰ to 37‰.

In addition to the above salts, few other elements and salts are also found—iodine, fluorine, arsenic, boron, lithium, caesium, barium, strontium, manganese, nickel, cobalt, zinc, lead, silver, gold and radium. But the percentage concentration of these is too small for precise measurement, though the total quantity present is great. It is worth noting that there are thousands of millions tons of gold and 1400 tons of radium in solution in the sea water.

¹ According to Murray (1887) sea water contains 5 billion tons of salts; Clarke mentions that 2.7 billion tons is carried by rivers into the sea.

ORIGIN OF SALTS IN THE SEA

It has been estimated that from the very beginning the crust of the earth is subject to slow dissolving action of water. Ever since sea water has been constantly washing the shores, and rains falling on the land have been draining into rivers and seas. Thus sea water contains all the elements of the earth's crust.

The rivers bring about 5.4×10^8 of the total solids of the ocean. But it is a curious fact that there is little similarity between the chemical composition of river water and that of sea water. The latter has chloride in abundance (about 75%) while the former has mostly calcium (60%). There is only 2% of sodium chloride in river waters. This shows that rivers either do not bring enough salts to the sea by which it is saline or that what they pour in the sea is continually being lost. The quantity of salts brought by the rivers is too small and estimated to be two millionth part of the total salt in the ocean. Some of it is absorbed by animals and plants to form skeletons of lime or silica. A certain proportion called cyclic salts is swept off the sea towards the land by wind blow sprays and picked up by water vapour and again brought into the sea. Thus they further reduce the gross contribution of salt which the rivers make to the ocean. Moreover, a great amount of calcium brought by rivers is constantly being withdrawn by marine animals like coral polyps, foraminifera, oysters, etc. In spite of the above facts the small amount of salt brought annually by rivers increases the salinity of the sea.

Salinity is also increased either due to erosion of the earth crust or by some agencies which add minerals from the obscure sources buried deep within the earth, e.g. volcanic ash brings some material—especially chlorine, boron, sulphur and iodine.

CONTROLS OF SALINITY

The amount of salt in the oceans is not similar everywhere due to varying factors which control the amount and distribution of salinity.

Evaporation. Okada, the Japanese investigator, has carefully observed the influence of rate of evaporation on salinity, and the various factors controlling its distribution. Evaporation is directly related to the amount of salinity in the sea water, as the salts left behind after continuous evaporation increase the salinity. According to Wust, the total evaporation from the ocean amounts to $334,000 \text{ KM}^3$ per year, though it is excessive in regions of higher temperature, strong steady winds, and less rainy days. The average evaporation from all the oceans according to Wust amounts to 93 cm. per year, while W. Schmidt computes it to be 76 cm. per year. The process of evaporation in fresh water depends upon temperature,¹ whereas in the ocean water salinity decreases the

¹ Okada found that sea evaporation was about 95 per cent of that of fresh water, the annual variations ranging from 92.6 to 96.8 per cent.

vapour tension slightly. Hence the ratio between the temperature and the humidity gradients of the air, at a short distance from the sea surface, varies from one part of the ocean to the other. The ratio is small in low latitudes or nearly constant throughout the year, but greater in the middle latitudes. Thus due to excessive evaporation and higher temperature, humidity ratio in the lower middle latitudes near Tropics of Cancer and Capricorn is lower and salinity is higher. On the other hand, salinity is comparatively low in equatorial regions due to evaporation and high relative humidities.

The evaporation varies from the eastern to the western parts of the ocean and also from one season to another. Again, it has diurnal variations which are computed by Kimball and Helland-Hansen. Okada and Mill concluded that evaporation proceeds on the average nearly two and a half times more quickly in sun light than in the shade. Further, with strong winds like trade and westerlies, evaporation also increases. Millar (1937) and Montgomery (1940) have computed that at wind velocity below 4 to 5 cm/sec. (10 miles per hour) the evaporation is relatively small, due to stable stratification of the air and comparatively smooth sea surface.

It also appears that evaporation will also take place owing to unstable stratification of the very lowest layers of atmosphere, if the water of the sea is warmer than the air. It must, therefore, be kept in mind that greater evaporation is expected when cold air flows over warm water. But it will take place only if the air is not saturated with water vapour.

Thus we see that as evaporation depends on a variety of factors, salinity is also indirectly determined by these factors and a great disparity is found in its distribution.

Precipitation. It is another factor which leads to diversity in the amount of salinity. In equatorial regions, in spite of high temperature, the salinity is less because these are zones of heavy rainfall which flows to the sea as the surface water and so leads to an appreciable reduction of salinity. North and south of this intra-tropical zone of calms, high temperature and heavy rainfall there are strong north-west and south-east trade winds. Hence there is an increase in evaporation resulting in an increase in salinity.

Again, in polar and sub-polar regions there is an excessive amount of precipitation of water from the atmosphere in the form of snow. This accumulates on the land and solidifies in the form of ice. Thus ice passes into the sea as glaciers and icebergs and, on melting in the temperate latitudes, adds fresh water to the sea and hence reduces salinity. In the Atlantic and the Pacific oceans during northern summers the surface water is more salty in regions where evaporation is greatest (probably the sub-tropical belt) and less in regions where dilution by snowfall or rainfall is greatest (equatorial and westerly belts). Round the poles there is a belt of low salinity which is due to the melting of vast fields of ice.

River water. The amount of salinity in sea water also varies due to the influx of fresh water by rivers. Hence near the mouths of rivers

Amazon, Congo, Niger, Ganges and St. Lawrence, comparatively lower salinity is found. The effect is also clearly seen along the coasts in the enclosed seas. In the Baltic Sea, many rivers from the land pour down fresh water in the Gulf of Bothnia and reduce the salinity to 5‰. Similarly many big rivers, such as Danube, Dneister, and Dnieper, fall into Black Sea and the salinity is found to be 18‰. On the other hand salinity is as high as 40‰ in the Mediterranean where evaporation is more than the influx of fresh river water. Further, in the enclosed dependent seas, during periods of maximum run off from the land, salinity of surface waters will be less than usual, while during periods of minimum run-off it will be greater.

Atmospheric pressure and wind direction. Salinity also changes due to winds resulting from difference in atmospheric pressure. There is a prevailing low pressure over Baltic Sea as compared to the North Sea. To compensate it, a great amount of water from the latter, having low salinity, comes into the former whose salinity is thus lowered. Off the Californian coasts, north-east trade winds drive away the warm saline water far off the coast, and consequently colder and less saline water swells up from the bottom. In the smaller seas, heavy storms may bring conditions which result in surface mixing of water and lowering or increasing of salinity. The strong winds blowing throughout the year carry much of the warm and saline water from the western shores of the land in lower middle latitudes and from the eastern shores in the higher latitudes, resulting in changes in salinity distribution.

Movement of sea water. It leads to a very thorough mixing of the surface water, and hence determines salinity. Among these movements are, firstly, the tidal currents which everywhere surge backwards and forwards in the neighbourhood of the land; secondly, currents and drifts which actually carry warm and saline waters from the equator to the pole, from the western coasts to the eastern coasts, from open seas to the dependent seas; and thirdly, the vertical movement which lifts up water from the bottom to the surface in some regions and causes surface water to sink to the bottom elsewhere. This mixing, when it is permanent and long continued, would lead to an absolute uniformity of composition at the surface. Had there not been other factors, uniform salinity would have been found in all the oceans. The currents, stirred by wind, sweep away the saline water from the eastern coast of the high latitudes to the western coasts, whereas cold water penetrates into the lower latitudes. These factors thus cause mixing of water and changes in salinity distribution. However, in the open sea, this mixing is comparatively easier than in the enclosed seas. The latter have lesser communication with the open sea and therefore salinity increases, e.g. the higher salinity of the Mediterranean which is separated from the Atlantic Ocean by narrow Gibraltar strait. On the other hand, those enclosed seas which have a wide opening to connect them with the open sea have variations in salinity in relation to the currents. Thus the waters of the Norwegian and the North seas are comparatively more saline due to the influx of the waters of Gulf Stream. Similarly, the Gulf of Mexico also has water of higher salinity, as warm and considerably saline equatorial water enters the region of sub-tropical dry latitudes in an

enclosed boundary. High saline water outflowing from Mediterranean Sea also increases the salinity of the Bay of Biscay and the English Channel.

According to Wust, the surface salinity is not a result of complicated phenomenon but depends upon the interaction of three factors: (i) decrease of salinity by precipitation; (ii) its increase by evaporation; and (iii) changes by the process of mixing. He pointed out that average values of the surface salinity can be computed by the evaporation and precipitation proportions. These two factors were clearly related to the atmospheric changes in circulation. For each ocean the deviation of the surface salinity from a standard value is directly proportional to the difference between evaporation and precipitation of that area.

Periodic variations of salinity. The variations in salinity are according to the nature of the atmosphere, i.e., the difference between precipitation and evaporation as related to the months of the year. Böhncke has computed the periodic variations in salinity in the North Atlantic between 18° — 42° N to be 36.70‰ in March (highest) and 36.59‰ in November. This annual variation in salinity is due to the nature of evaporation, i.e., higher salinity is found at the end of June, while minimum occurs near about December when evaporation is at its minimum. As a whole salinity is higher in spring than in fall. In coastal areas, salinity varies according to the influx of fresh water by rivers; in lower latitudes it is increased in July and August, while in higher latitudes it is increased during spring and summer. Diurnal variations also influence salinity but they are too small to register.

Yearly periodic variations are clearly noted in the enclosed or dependent seas which easily react to the nature of the atmosphere. Near the East Indies Sea, the variations in salinity are related to the shifting of the trade wind belt and the occurrence of typhoons.

DISTRIBUTION OF SALINITY

HORIZONTAL DISTRIBUTION

(i) **Latitudinal.** Salinity is primarily controlled by latitude, and consequently decreases from the equator towards the poles. It is not maximum at the equator due to excess of rain over evaporation, but the region of 20° — 40° N records the highest average salinity of 36‰ as a result of higher evaporation. In the southern hemisphere between 10° — 30° S, 36‰ salinity is found. After obtaining maximum in the lower middle latitudes it again decreases between 40° — 60° N and S and is 31‰ in northern hemisphere and 33‰ in southern hemisphere. Still lesser salinity is found in the polar areas due to the melting of ice. However, for the whole of northern hemisphere the average salinity observed is 34‰ and in southern hemisphere it is 35‰ . The difference in these two is attributed to the abundance of ocean water in the southern hemisphere and comparative ease of mixing due to absence of any land barrier. Salinity for different latitudes as calculated by Johnstone is given in Table 2.

There is roughly low salinity in the equatorial zone; high in tropical belts north and south; low salinity in the temperate zone; minimum salinity in the sub-polar zone.

The coastal waters all along the continents record lower salinity as compared to the central part of the sea due to addition by fresh water. In the open sea, salinity differences depend on the currents and mostly vary according to the latitudes. But inland seas and dependent seas do not follow the principle of latitudes. In middle latitudes partially enclosed seas exhibit highest salinity (depending on evaporation factors), whereas in higher latitudes their salinity depends not on the latitude but on the influx of water, e.g. the North Sea records comparatively higher salinity than the Baltic Sea, though both extend between same latitudes.

TABLE 2¹

Zones of Latitude	Salinity ‰
70°—50°N	30—31
55°—40°N	33—34
40°—15°N	35—36
15°N—10°S	34.5—35
10°—30°S	35—36
30°—50°S	34—35
50°—70°S	33—34

Regional. The world distribution of surface salinity would, in fact, present a detailed picture of horizontal salinity among various oceans. Jenkins has classified the oceans according to salinity as shown in Table 3.

Atlantic Ocean. The average salinity in this ocean is 35.67‰ but it is not found at the surface near the equator. North of 5° N it is 34.98‰ and again it increases to 36‰ upto 15° N. In the South Atlantic in similar latitudes comparatively higher salinity is found ranging up to 37.77‰. There are two regions of higher salinity north and south of this zone of lower salinity. The northern region has its centre roughly about 25° N and 40° W while the southern one is about 15° S and 25° W along Brazilian coast. Around these central areas the salinity decreases to 35‰ though this decrease in both the parts of the ocean is not uniform.

Further north in higher latitudes in North Atlantic, the eastern part records higher salinity due to the transportation of the main saline water of the Gulf Stream towards the west. Hence the isohalines are pressed higher in north-east and 35‰ saline water is found at 70° N near Spitsbergen, while low saline water penetrates in the form of Labrador current on the western shores of the North Atlantic Ocean. Similar lowering of salinity is found on the west coast of Africa along Gulf of Guinea (in sub-tropical region) where upwelling of cold water is found (as trade winds drive warm and saline water to the west part of the ocean). On the eastern coast of America north of 35° N salinity decreases

¹ Johnstone, *An Introduction to Oceanography*, p. 140.

TABLE 3

*Examples of Seas, classified according to salinity*¹

Above normal	Normal	Below normal
Red Sea (37—41)	Caribbean-Mexico (35—36)	(a) <i>Slightly less</i>
Persian Gulf (37—38)	Bass Straits (35½)	Arctic Ocean (20—35)
Mediterranean Sea (37—39)	Gulf of California (35—35½)	North Australian Sea (33—34)
		Bering Sea (28—33)
		Sea of Okhotsk (30—32)
		Sea of Japan (30—34)
		China Sea (25—35)
		Andaman Sea (30—32)
		North Sea (31—35)
		English Channel (32—35)
		Gulf of St. Lawrence (30—32)
		(b) <i>Much below</i>
		Baltic Sea (3—15)
		Hudson Bay (3—15)

to 32°/00 south of Newfoundland, and to 32°/00 and 31°/00 in Davis Bay and Norwegian coast respectively.

In the South Atlantic, isohalines are mostly found parallel to the latitudes due to excess of water over land. Here the 40th parallel is approximately the southern boundary of water which has a salinity of 35°/00 or more. In the South Atlantic between 10-30° S, more saline water is found mostly on the western shores, while cold water upwells in the eastern part. At the river mouths also specially low salinity is found: St. Lawrence 31°/00, Amazon 15°/00, Congo 34°/00, Niger 20°/00, Senegal 34°/00 and Rhine 32°/00.

In partially enclosed seas of the Atlantic, salinity is dependent on factors other than those prevalent in the open sea. In the North Sea it is 34·0°/00 which is comparatively higher than other enclosed seas due to an influx of gulf branch into it, but lower than the surrounding sea due to lesser evaporation. In the cold seas of higher latitudes, where rainfall and-river influx is greater, salinity is minimum as in the Baltic. There is a decreasing salinity with the increasing distance from the North Sea. About the island of Rügen it is only 7 or 8°/00, whereas near the Gulf of Bothnia and the Finland coast, due to debouchure of river Oder and

¹ Jenkins, *A Text Book of Oceanography*, p. 10.

Vistula, it is less than $2^{\circ}/_{00}$. Towards the east of south Sweden it is $11^{\circ}/_{00}$ and off Bornholm $8^{\circ}/_{00}$.

In the Mediterranean, evaporation is comparatively greater and mixture with open sea water is less. At the Gibraltar Strait the salinity is $36.5^{\circ}/_{00}$. Towards the east it increases to $39^{\circ}/_{00}$ near Egypt and

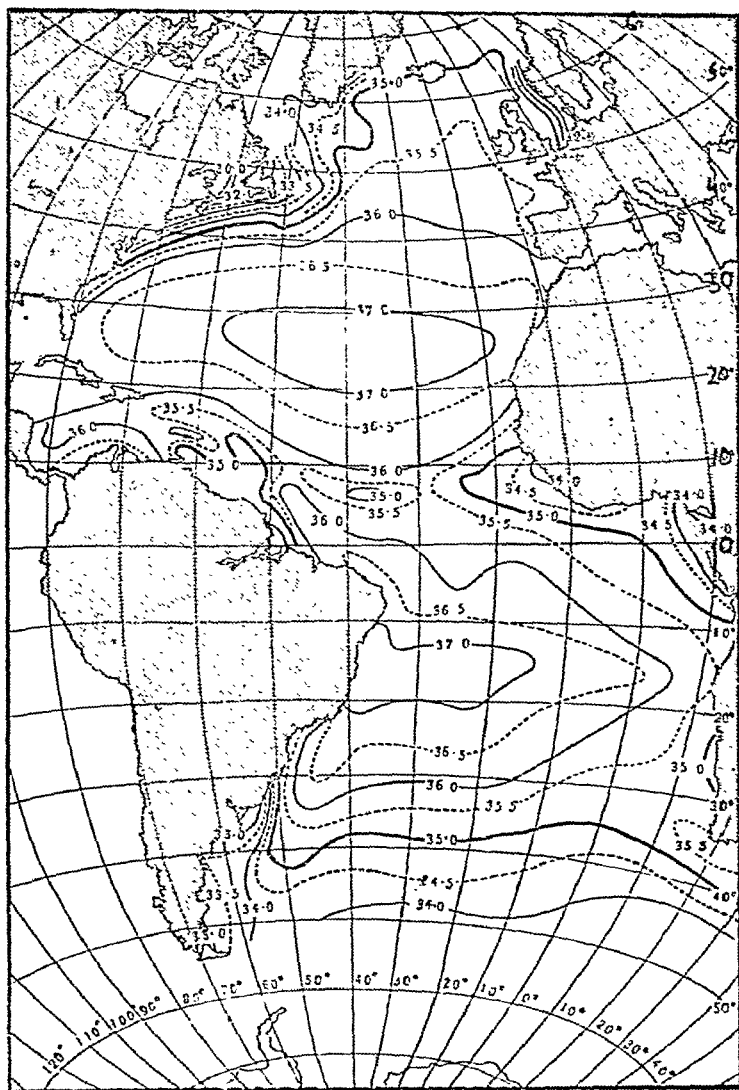


Fig. 55. Surface Salinity of the Atlantic Ocean (in northern summers).

Israel, whereas in the Black Sea, due to greater mixture of fresh water through rivers, it is lower and is between $17^{\circ}/_{00}$ and $18^{\circ}/_{00}$. In the Gulf of Mexico and the Caribbean Sea, higher saline water amounting to $36^{\circ}/_{00}$ is found due to the warm saline water of equatorial region.

Indian Ocean. The observations in this ocean are comparatively less. Between 0° — 10° N, less saline water ($35.14^{\circ}/_{00}$) is found. Salinity decreases towards the Bay of Bengal reaching up to $30^{\circ}/_{00}$ at the mouth of the Ganges. But towards the Arabian Sea, drier conditions prevail and lesser amount of water is added by rivers, hence an elliptical region

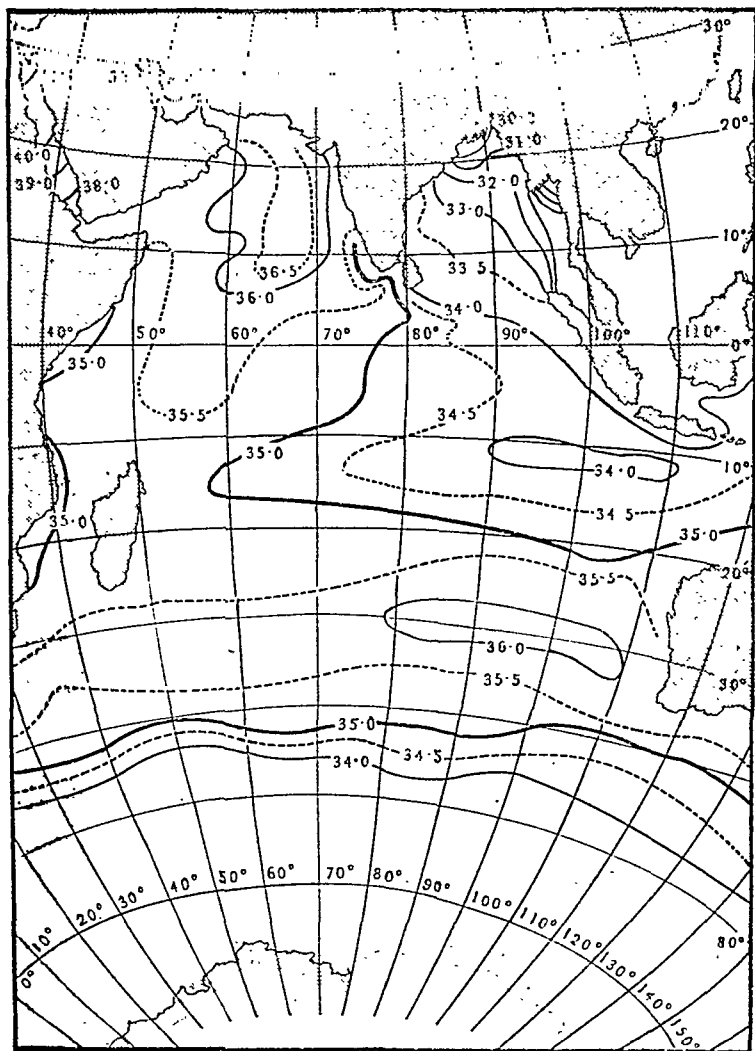


Fig. 56. Surface Salinity of the Indian Ocean (in northern summer).

of higher salinity of 36‰ is found. South of Equator where average salinity is 35‰ , a longitudinal region of 34.0‰ salinity is found south of Java island. The maximum salinity in the southern part is found west of Australia due to dry conditions. Generally isohalines in the Indian Ocean run more parallel to the Equator than in the Atlantic. Again, at the mouth of rivers the salinity is low: at Ganges mouth 30‰ , Irrawaddy 20‰ and Euphrates 35‰ .

In the partially enclosed seas of the Indian Ocean, the Red Sea and the Persian Gulf are important. At the head of the latter it is

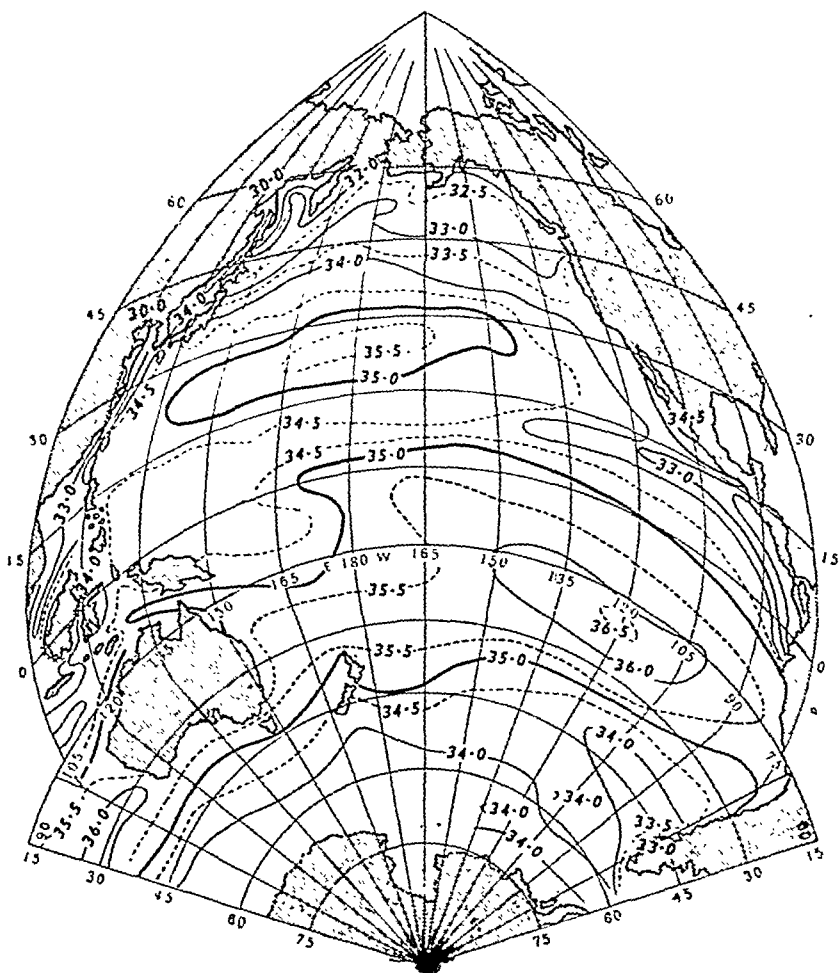


Fig. 57. Surface Salinity of the Pacific Ocean (in northern summer).

37.0‰ while in the interior it amounts to 40.0‰. The Red Sea records perhaps the highest salinity due to high evaporation and lesser precipitation and mixture. At the head near Bab el-Mandeb, the salinity is 36.5‰ and near the Gulf of Suez it is 41.0‰.

Pacific Ocean. The Pacific Ocean is slightly different from the other oceans due to its shape. At the equator, the salinity is 34.85‰, whereas north and south of this between 15°—30° latitudes elliptical areas of high salinity are found—maximum of 35.0‰ in the north-western and central part of the North Pacific and comparatively higher salinity of 36.0‰ in the South Pacific. North of this along the western margins of the ocean salinity is decreased to 31‰ in Okhotsk and 34‰ near Manchuria due to (i) the influx of cold and fresh water of Oyashio current from the Bering Strait as a result of ice melting, and (ii) the disappearance of warmth of Kuroshio current. Consequently, an easterly projection of the tongue of low salinity is found in the eastern side in the tropical latitudes along central American, Californian and the Peruvian coast due to upwelling of cold water. Similarly, in the South Pacific, south of the area of higher salinity in 20° S and 120° E, lower salinity is found along the Chile and the Peru coast. Along the Columbian coast, salinity is 28‰ and in south Chile 33‰. To the south, the salinity in the open ocean decreases to 34‰. Further, river mouths like Hwangho and Yangtze-kiang record lower salinity amounting to 30‰ and 33‰ respectively.

Inland seas and Lakes. The degree of salinity increases in a lake or in the inland sea due to the absence of any outlet, more evaporation and little addition of river water. Therefore, salinity in an inland sea increases with its age. Great Salt Lake in Utah has a salinity of 220‰, Red Sea 240‰, Lake Van in Asia minor 330‰. In the northern part of the Caspian where Volga and Ural rivers fall, salinity is less than 14‰ but in the shallow Gulf of Karabugas it reaches up to 170‰.

VERTICAL DISTRIBUTION

Salinity in the ocean decreases or increases in the bottom according to the nature of the water mass. Those who attribute salinity to the atmospheric reaction conclude that due to the greater depth and less radius of influence of the atmosphere, salinity decreases at the bottom. This variation in salinity shows large difference with the latitude unless there is an occurrence of some cold or warm water mass which may result in drastic changes. At the southern boundary of the Atlantic, salinity is 33.0 but at 200 fathoms it increases to 34.50, still deeper at 600 fathoms it reaches up to 34.75‰. At 20° S the surface salinity of 37‰ decreases up to 35‰ at the bottom. Just at the Equator the surface salinity of 34‰ increases with the depth to 35‰ due to greater mixture of fresh water at the surface. A map of Gibraltar Strait would illustrate that the rate of decrease even on two sides of the strait in the Atlantic and the Mediterranean is not similar. At the entrance of Mediterranean 36.50‰ salinity is found which continues still up to 600 fathoms. This shows that no fixed rule can be deduced as regards the decrease of salinity with depth.

Further, the increase in the amount of salinity according to the increasing depth is not same in the North and South Atlantic. This can

be very well seen in Figs. 58 and 59. They show slower rate for the South Atlantic Ocean in comparison to the North Atlantic Ocean.

Generally, it can be said that in high latitude, salinity increases with depth due to dense water found at the bottom, whereas in the middle latitude salinity increases with the depth up to 200 fathoms and then it starts decreasing. At Equator due to a mixture of fresh water by rainfall, surface salinity is low. Just below this greater salinity is found which again decreases at the bottom due to the presence of cold water.

Vertical sections of the Pacific in Fig. 60 and of Indian Ocean in Fig 61 also reveal the distribution of salinity in the oceans. The rate

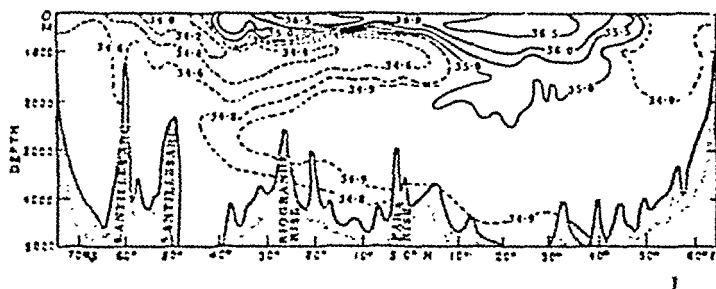


Fig. 58. Vertical section showing distribution of salinity in western Atlantic Ocean (After Wüst).

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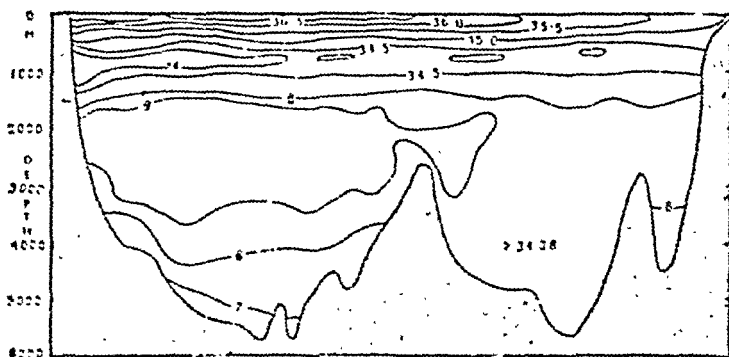


Fig. 59. Vertical section showing distribution of salinity in the Southern Atlantic Ocean (in about 20°S latitude).

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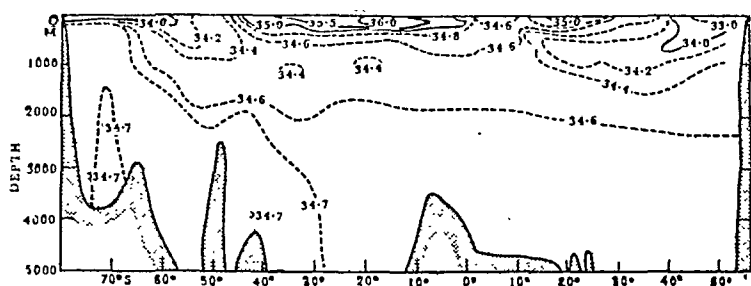


Fig. 60. Vertical section showing distribution of salinity in the Pacific Ocean (Along the meridian of 170° W).

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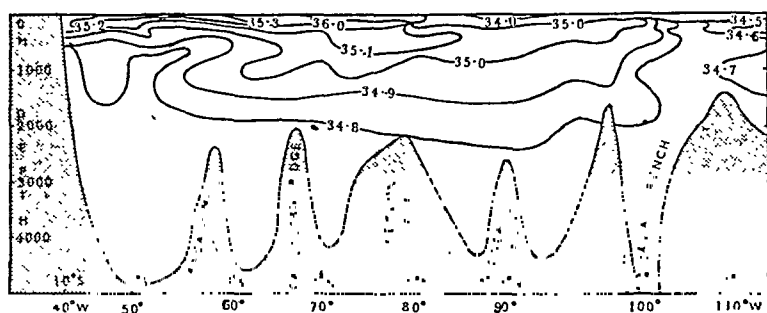


Fig. 61. Vertical section showing distribution of salinity in the equatorial region of the Indian Ocean.

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of increase in the amount of salinity with the increasing depth is rather irregular and significant up to the depth of 2000 m. after which it becomes almost insignificant.

Chapter 10 | DENSITY OF SEA WATER

The density of any substance is the mass (weight) per unit volume stated in grams per cubic centimetre. Commonly the word density is used for specific gravity which is "the ratio of the density to that of distilled water at a given temperature and under atmospheric pressure." Pure water has maximum density of one unit at temperature 4°C , whereas for the sea it changes according to the salinity content.

The density of pure water depends upon temperature and pressure only, whereas that of sea water depends upon temperature, pressure and salinity. If sea water at a fixed temperature and pressure is found to be varying in density, it may be attributed to salinity variations. Moreover, other factors like convergence etc. also control the density.

CONTROLS OF DENSITY

Temperature. In all the oceans, the range of temperature found is from -2° to 30°C , the lower limit being determined by the formation of ice, and the upper limit by the process of radiation and exchange of heat with the atmosphere. The thermal expansion varies with the increase and decrease of temperature. The former leads to the expansion of water particles with consequent lowering of density. Contrary to this, cool waters of low temperature cause shrinkage of the ocean waters and an increase in density. Due to this fact the waters of tropical latitudes have lower density as compared to those of temperate and polar waters. But warm water is not always of low density because, apart from temperature, salinity is also an important determinant. Moreover, it is generally found that warm water of high salinity attains higher density after suddenly being cooled. An example is afforded by Gulf Stream which attains greater density after entering higher latitudes.

Salinity. The second controlling factor of the density of sea water is the amount of salinity present in it. The dissolved salts increase the weight of the water sample and thus the density of the layer is increased. The freezing point temperature, the temperature of maximum density, and the osmotic pressure are dependent on salinity which in its turn changes the density of sea water. It is calculated that if average salinity is 35‰ , the density will be 1.028 .

Highly saline waters of greater density are mostly found in areas of excessive evaporation and less mixing with fresh waters. Such conditions are found in enclosed seas or dependent seas like the Caspian Sea, the

Red Sea and the Mediterranean Sea. The saline water of higher density is also found at places where it meets cold water and freezes abruptly. The dense saline water of the Mediterranean is the result of winter cooling. As salinity declines, the water becomes relatively less dense due to the absence of solid particles which increase the weight of sea water.

Pressure. Atmospheric pressure is considered to be an important factor which modifies density. With increase of atmospheric pressure, the specific heat¹ of the water is increased and compressibility is found over the layers of the ocean water. It is calculated that for the sea water of 35‰ salinity and 0° temperature, the co-efficient at atmospheric pressure is 51×10^{-6} .

The changes in pressure result due to changes in temperature and salinity. The former is directly controlled within the atmosphere resulting in the consequent changes in the density of ocean waters. It is found that higher is the temperature of atmosphere, lower will be the atmospheric pressure, hence lesser will be the specific heat. Thus at high atmospheric pressure specific heat will also be higher and the temperature lower. If the salinity of sea water is 34.85‰, the specific heat equals to 0.941 at 0° C and 0.932 at 20° C. Specific heat also changes according to the changes in the pressure of atmosphere. At 4000 decibars, it equals to 0.970 for 34.85‰ salinity at 0°C.

Thus we see that the atmospheric pressure, with the help of temperature and salinity, has direct effect on the compressibility of the layers and on the density of sea water. If the temperature is high, pressure is low and salinity is high or low, the result would be lower density of the ocean water. On the contrary, with low temperature, high pressure and low salinity, the density of sea water would be higher.

Convergence. The density also increases or decreases according to the convergences or divergences in the ocean water. These two oceanic movements are related with atmospheric convergence and divergence resulting in high pressure and low pressure respectively.

Similar types of density differences are found in areas where upwelling and shrinking is found. In the former higher density is recorded at the surface, while in the latter lower density is at the surface but higher prevails at the bottom.

DISTRIBUTION OF DENSITY

In general, there is a latitudinal difference in the density distribution, depending on the character of the water changing from the Equator to the Poles. The density of the upper layer commonly increases from the tropics towards the Poles.

The nature of the comparatively dense water is to sink down below lighter water. When two water masses having different density meet, the denser sinks downward and then spreads out from the place where similar density is found. It is observed that in the middle latitudes, the denser water sinks at lesser depths than the water that sinks at convergences in higher latitudes.

¹ Specific heat is the number of calories required to increase the temperature of one gram substance by one degree centigrade.

Again, at surface the density decreases according to heat, lower atmospheric pressure, and low salinity, but it increases by cooling, higher atmospheric pressure and high salinity. Thus these factors found in varying proportions from the Equator to the Poles control the density distribution of ocean water.

Horizontal distribution. The excess of heat in the equatorial parts results in the rise of convective currents within a thin upper layer. Hence the upper water of low salinity expands and there is no possibility for upwelling of colder or denser water from the bottom. This also retards the mixing of water, and the surface density remains low in comparison with the density at the bottom. Further, in the lower latitudes open sea water remains at a low density due to the mixture of fresh water. But in this region some insulated adjacent seas record higher salinity and higher density as a result of greater evaporation and less amount of fresh water being added by rivers. Such examples are afforded by the Mediterranean Sea, the Red Sea, and the inner part of the Gulf of California. In these areas even a moderate cooling in winter leads to the formation of dense water at the surface and bottom, which moves outward into the open sea.

In the middle latitudes, due to the excess of precipitation and low salinity, the water has lower density. Here the development of convective currents is prevented and there is no mixture with the dense water at the bottom. Only in a few cases dense waters are found in these latitudes.

(a) Whenever the water of high salinity is carried by the currents into middle latitudes and is cooled, the density increases. This mixed water has a relatively high salinity, and when it is further cooled in winter, convective currents that may reach from the surface to the bottom develop before any freezing of ice begins. In this manner the bottom water is formed having high salinity and a temperature that lies several degrees above freezing point of water. Such conditions are found in the North Atlantic Ocean when the Gulf Stream with high salinity comes in contact with less saline and cold waters of the Labrador on the eastern side and with Norwegian waters in the Irminger Sea on the western side. Similar process is also found in the Japanese Sea where Kuroshio meets the cold Oyashio and Kurile currents.

Similarly, in higher latitudes those regions record high density where salinity of the incoming water is higher and freezes during winters. In the Arctic Ocean excess of fresh water from the Siberian rivers maintains low salinity and therefore freezing does not increase the amount of salinity and density sufficient to form bottom water. But around the Antarctica, where there is no mixing of fresh water, continental freezing in the months of winter helps to increase the density of the water and the formation of homogeneous dense bottom water. Only those regions are left behind which record high precipitation.

(b) Convergence also creates dense water at the surface. There are three types of convergences found at the surface: tropical, sub-tropical

and Antarctic-Arctic convergences. In the tropics temperature and salinity of the surface is low and therefore in spite of convergences in such latitudes, density is not increased. Here the mixing of water does not take place as a result of surface water sinking, so the denser water only develops at some distance below the surface.

In the areas of sub-tropical convergences, ordinarily the density of the upper layer increases towards the pole. Now when this moving water converges with the cold and less saline water of higher latitudes, the sinking of water takes place as both of them are of different densities. There surface water also records higher density than that of the surrounding areas.

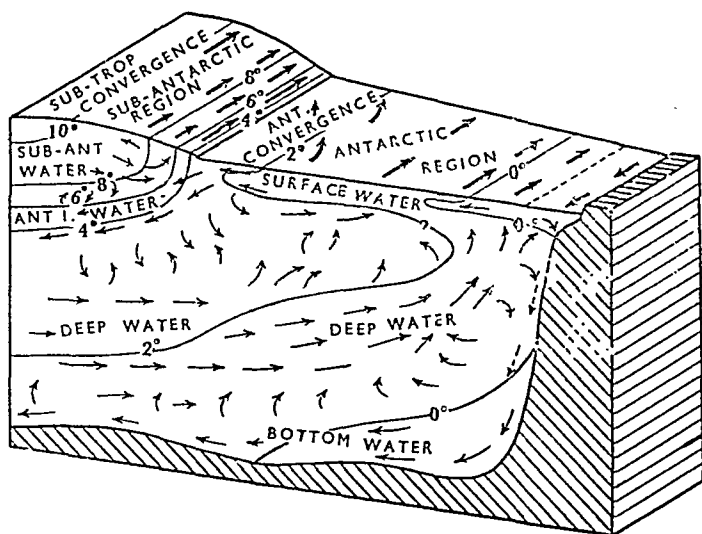


Fig. 62. Schematic representation of the currents and water masses of the Antarctic region and of the distribution of temperature.

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But most conspicuous convergence that creates changes in density of sea water is found in the Antarctic convergence region around the continent of Antarctica. The sinking of water takes place as a result of the mixing of freezing water of the Antarctica with that of comparatively warm water from lower latitude. Deacon attributes the Antarctic convergence to the character of deep water circulation. He points out that convergence is found where the relatively warm but deep saline water rises, and he argues that within the Antarctic region the upper water, being heavier than the warm surface water further north, would sink if it was not prevented by the highly saline deep water. Sverdrup, on the other hand, suggests that the convergence is brought about because in the

Sub-Antarctic region a thermohaline circulation dominates which would carry the light surface water to the south, whereas in the Antarctic region a wind circulation dominates which would carry the surface water to the north. Thus the water of relatively low salinity and low temperature sinks at the Antarctic convergence and gradually mixes with the underlying deep water between 800 and 1200 m. depth in the form of Antarctic intermediate water. In the Arctic convergence dense mass is not so well developed as in the North Atlantic Ocean, though in the North Pacific Ocean a small mass of Arctic intermediate water is present and sinking takes place at the surface.

(c) The ascending motion of the water at some places also creates water of high density. Along the western side of the continents in lower latitudes and on the eastern coast in higher latitudes upwelling of deep water takes place as a result of deflecting of surface water under the stress of trade and westerly winds. Such upwelling of cold water takes place near the Californian coast, the Peruvian coast, and the eastern coast of America. Similar process also takes place near the Antarctica continent in the South Atlantic in order to compensate for that water which has sunk due to convergence.

Vertical Distribution. Generally vertical distribution of density resembles somewhat the average horizontal distribution from the Equator to the pole, with slight regional changes. The vertical distribution of density would reveal that generally at surface waters of low density are found which increase in density towards the bottom. It is so because any amount of water which finds itself among less dense water would sink automatically below the surface up to that depth where water of similar density is found. Hence at places of convergences, dense water mass sinks below the lighter one and forms bottom water. Nevertheless, contrary to the surface current from the Equator towards the pole, there is a bottom current from the pole towards the Equator and this brings denser water under the surface of the sea.

STRUCTURE OF THE OCEANS

Vertical. Comparable to the atmosphere there are also structures in the ocean. In high latitudes, whole water mass from the top to the bottom has low temperature and low salinity. Hence the density remains stable all over the area with slight increase towards the bottom and no clear vertical structure is found. In the lower and middle latitudes, there are two prominent layers like that of atmosphere—the troposphere and the stratosphere. The former is the warm, saline water of low density with strong currents, while the latter is nearly a uniform mass of cold deep bottom water of high density. These structures are clearly defined by three water masses—the upper water mass of low salinity, high temperature and low density; the intermediate water mass of comparatively high density; and the bottom water which is a dense mass of polar seas. In high latitudes this intermediate water is lacking and only upper and lower waters are found.

Horizontal. The study of horizontal structure of the oceans and the water masses is as important in Oceanography as the

concept of air masses in Climatology. Water masses may be defined as those bodies of sea water which have a particular temperature, salinity characteristics, and a quasi-horizontal boundary. Helland-Hansen stressed the use of Temperature-Salinity (T-S) diagram in order to delimit the water masses. He avoided the density consideration because according to him it is not necessary that waters of similar temperature and salinity may have the same density. Consequently, water masses of different temperature and salinity may also have the same density. He observed that temperature and salinity curves of the sub-surface water showed remarkable coincidence; hence water masses could be divided according to them.

But some facts must also be kept in mind while discussing about water masses. The water bodies mostly gain their characteristics by continuous contact with the atmospheric radiation. Secondly, due to lateral and vertical mixing of water, the boundaries and the character do not remain stable. Hence there is a perpetual tendency to create a homogeneous water mass. Again, a water mass of uniform temperature and salinity is rarely seen in the open ocean. The denser water automatically sinks down and spreads at the bottom. The formation of this water mass will also not be uniform, as it depends on the nature of the surface water that sinks down and settles at various depths according to its nature. Here again mixing takes place. Generally the density increases at the bottom, and shows a particular T-S relationship while in the middle latitudes, according to Iselin, sinking may lead to the formation of such water mass which has a T-S curve that reflects horizontal temperature and salinity on the surface. Hence surface and sub-surface water have different T-S curves.

Vertical mixing. Vertical mixing also causes modifications in the character of a water mass. In the South Atlantic, the Antarctica intermediate water flows northward and loses its character of the source region, i.e. low salinity minimum, because of vertical mixing in the layers of the ocean. Defant has attributed this to the vertical mixing by which clear water masses far from their source region lose their identity. Sinking and upwelling are also methods of vertical mixing which create a totally different character of water masses at the surface or at the bottom.

Horizontal mixing. The result and the occurrence of horizontal mixing in the water mass is observed by means of T-S Index which shows a difference in its density from the surrounding water. Along the Californian coast, in between the two water masses flowing on north and south coast, the intermediate water has a totally different character from that of the surrounding area and is considered to be formed by lateral mixing.

Wüst by his 'core method' has helped to understand the cause and process of horizontal mixing. According to him, it is that layer in which temperature and salinity both reach extreme values, i.e. the layer of water having partial T-S ratio has high salinity, as found in the Mediterranean. This dense water moves towards the other region and forms a particular layer which could be traced in other oceans, e.g. the dense water of the Mediterranean resulting from horizontal mixing

moves into the Atlantic and can be traced far from its source region. But with the increasing distance from the strait, the original high salinity of the water disappears. The T-S curve located at the end of this water mass may help to find its boundary and movement. Mixing also occurs when 21.5 to 22°C temperature and 40.5 – 41‰ saline Red Sea water spreads through Bab el-Mandeb Strait into the equatorial water mass of the Indian Ocean.

DISTRIBUTION OF WATER MASSES

Due to Sub-Surface Mixing. The following water masses are formed by the process of sub-surface mixing.

1. *Equatorial water mass.* The equatorial water mass is a warm water, covered by a surface layer 100 to 200 m thick, within which temperature and salinity vary greatly due to seasonal variations in the atmosphere and character of the current. Average temperature ranges between 90 – 100° , with 35‰ salinity. In the Pacific and the Indian Ocean equatorial water

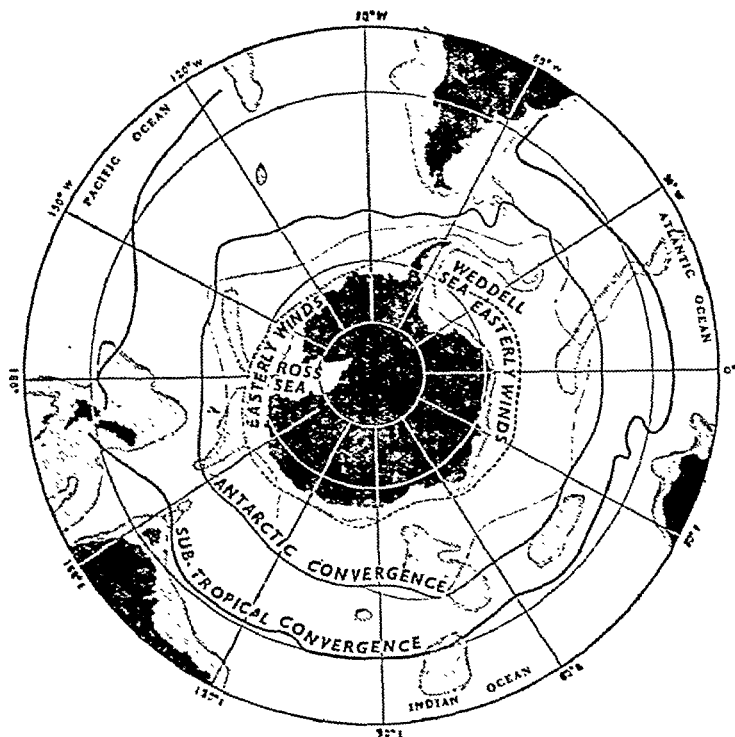


Fig. 63. The Antarctic and Sub-tropical convergences (After Deacon). Dashed line showing limit between westerly and easterly winds (light shading: depths less than 3000 m).

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masses are present along the equator. This mass is altogether absent from the Atlantic Ocean due to its particular shape.

2. *Antarctic Circumpolar water mass.* This water mass surrounds the Antarctic continent and is formed due to the mixing of the Atlantic deep water and Antarctica bottom water. It also includes the traces of Antarctica intermediate water and the Mediterranean water.

3. *Sub-Antarctica water mass.* In between the Antarctic convergence and the southern sub-tropical convergence, it represents the transitional water at the surface. All round the earth it has similar characteristics. In the South Atlantic, sub-Antarctic water mass is of low salinity formed by mixing and circulation (vertical) in the region between the two convergences.

4. *Sub-Arctic water mass.* Sub-Arctic Pacific and Atlantic water masses are formed in the north of sub-tropical convergence, mostly due to mixing. In the North Atlantic it is found in a small region which is of high salinity. In the North Pacific it is of wide extension and has low salinity. Along the west coast of North and South America in the Pacific Ocean, the sub-Arctic and Antarctic water is observed penetrating towards the equator. Here its character is changed due to heating and evaporation at the surface.

5. *Arctic and Antarctic convergence.* In the South Atlantic and the Pacific, the Antarctic convergence is a continuous and well-defined poleward boundary of sub-Antarctic water (Fig. 63). In the northern oceans, Arctic convergence is found in the western part of the ocean only, and in a large area no poleward boundary is found.

Due to Sub-Tropical Convergence. Between 35° – 40° N the convergence causes mixing and sinking to some extent and water masses are formed.

1. *Central water masses.* All the central water masses are mainly formed due to sinking in winter at the sub-tropical convergence in the latitude 35° – 40° S and N. Though they are not well defined, yet these masses are made of thin sheet, the greatest of all being 900 m in Sargasso Sea. In the Pacific, the central water mass is 200–300 m thick. These masses are vertically not much thick and extensive. Their average thickness is about 200–300 m and that too in the west of the oceans. In these areas due to decrease in temperature and salinity, the density increases with latitudes. Therefore, sinking of surface water forms bottom water. The T–S curve resembles the curve of the surface water in winter. But the water masses in all the three oceans, in spite of corresponding character, differ a lot. In different oceans T–S relations vary and cause differences in sinking and formation of the water mass (Fig. 64). Even in a single ocean, variations in water masses could be detected in eastern and western part. The following are the central water masses present in all the oceans :

(a) North Atlantic and South Atlantic central water mass. In between these two water masses there is no equatorial water mass. North Atlantic central water mass contains higher salinity as compared to that of the southern mass. It attains greatest thickness along the western

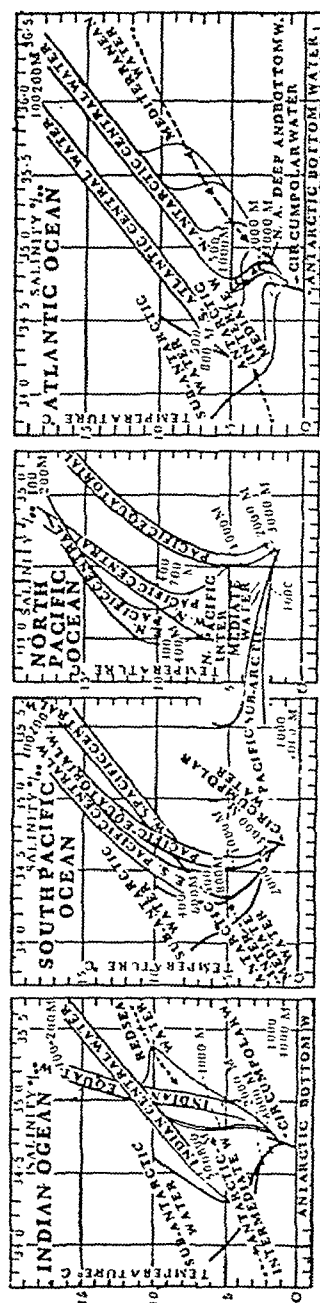


Fig. 64. Temperature—Salinity relations of the principal water masses of the oceans.

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boundary of the ocean, reaching a maximum of 900 m in the Sargasso Sea. Here salinity is also highest. The contrast with that of the south is due to the difference in evaporation, precipitation and character of the oceanic circulation. In this water mass considerable amount of mixing is also found in small regions. The water mass of the South Atlantic is comparatively of low salinity and density. Much of its water is diverted north of the equator. At the bottom of the ocean the sub-Arctic water of low salinity is found. In South Atlantic, cold water of Antarctic is traced around the Cape of Good Hope. Apart from the mixing with cold water, warm, dense and highly saline water of the Mediterranean ($13.0-13.6^{\circ}\text{C}$, $38.4-38.7\text{‰}$) flows out from Gibraltar and spreads below the North Atlantic central water mass.

(b) *Pacific Central Water Mass.* It occupies much of the area of the Pacific, north and south of the Equatorial water mass. In the North and South Pacific they are further divided into western and eastern central Pacific waters. This water mass is covered by a layer 200—300 m. thick. On the western margins of the North Pacific coast, sub-polar water advances along North American coast which is the transition region. The existence of separate water masses here is attributed to the separate high pressure areas in the atmosphere during winter.

In South Pacific Ocean, similar character of the central water mass appears. But the eastern South Pacific water mass records particularly lower salinity and higher density due to the appearance of the Peru current and upwelling of the sub-Antarctica water. The western Pacific central water has also comparatively lower temperature and salinity than that of the water masses of the Indian and the North Pacific oceans, due to the greater amount of saline water and the possibility of mixture. In general, the Pacific central water mass has low salinity as compared to the Atlantic water mass. Moreover, the vertical thickness of the mass is also less than that of the other oceans. The existence of sub-Arctic water in between the central water mass is particularly found in the western part of the ocean.

(c) *Indian central water mass.* In the midst of the Indian Ocean, this central water mass contains average temperature of 8°C and salinity 34.60‰ . It has similar characteristics as that of other oceans, but contains higher salinity than that of the Pacific Ocean.

2. *Antarctic bottom water.* In the south of Atlantic a bottom water develops which originates near Antarctic, specially around Weddell Sea. On the continental shelf the salinity is 34.62‰ , temperature 1.9°C and density 27.89, whereas the corresponding sea water has salinity, 34.68‰ , temperature 0.5°C , and density 27.84. The water therefore sinks along the continental shelf and mixes with the warmer and more saline water. When this water reaches the bottom it has 34.60‰ salinity and 0.4°C temperature. Such deep bottom water is found in the Atlantic and the Indian Ocean.

3. *North Atlantic deep bottom water.* This water mass has its origin in the Labrador Sea and between Iceland and Greenland. In this region, the warm and saline waters of Gulf Stream get mixed up with the colder and less saline water of the East Greenland current. During

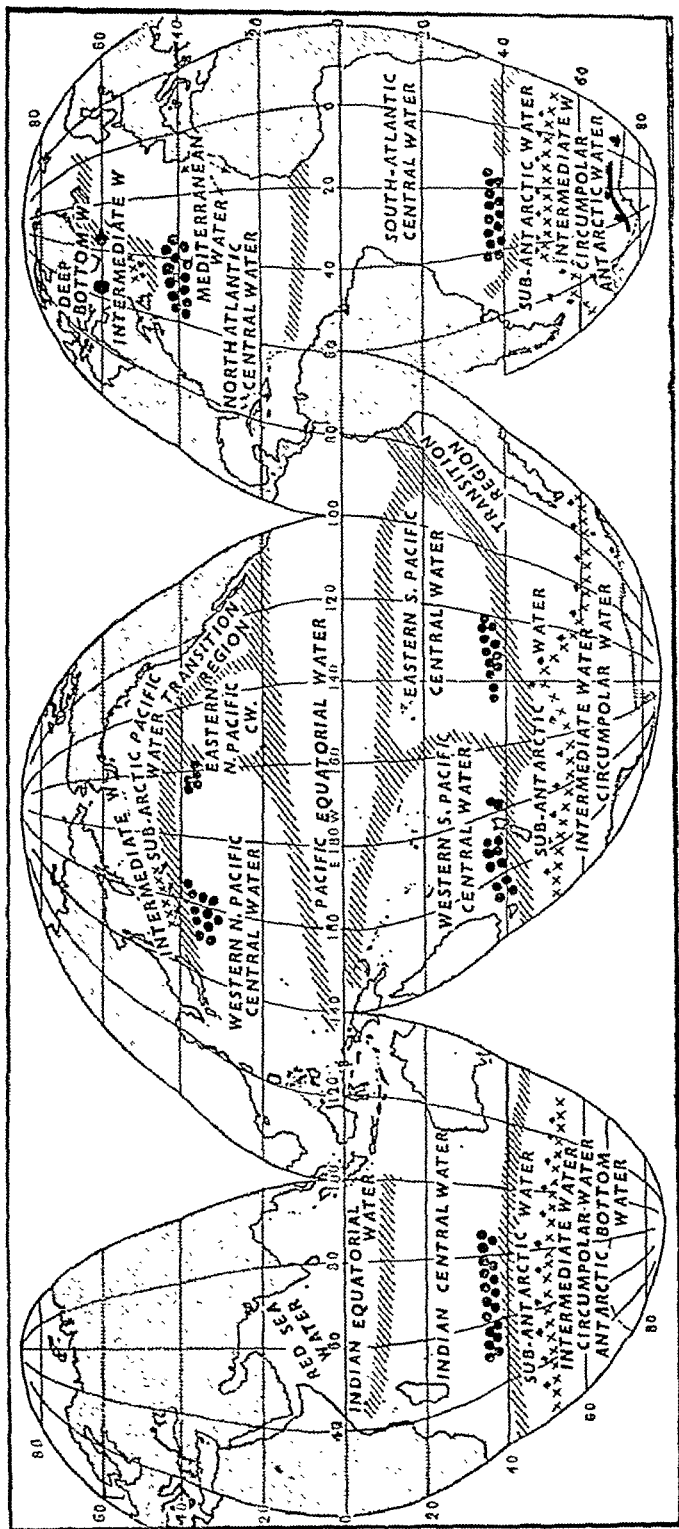


Fig. 65. Approximate boundaries of the upper water masses of the oceans (Black dots indicate the regions in which the central water masses are formed and crosses show the lines along which the Antarctic and Arctic intermediate waters sink).

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winters it is cooled at the surface and attains high density (27·88) enough to sink. Variations result due to a great deal of mixing and cooling and sinking of waters of different salinity, temperature and densities. The water that sinks below 1000 m has a salinity between $34\cdot90^{\circ}/_{00}$ and $34\cdot96^{\circ}/_{00}$ and temperature between $2\cdot8^{\circ}$ and $3\cdot3^{\circ}$ C. Deep water is formed at two places in the Atlantic, but not in the Pacific, as in the latter no water of high salinity is subject to intense cooling in winters.

4. *Antarctic intermediate water.* Having salinity of $33\cdot8^{\circ}/_{00}$, density 27·0 and temperature $2\cdot2^{\circ}$ C, the water at the surface sinks down at the Antarctic convergence to form intermediate water. It is found in the South Atlantic, the South Indian and the South Pacific oceans. A continuous belt of intermediate water is traced from east to west, within the belt of strong westerlies, and is characterized by minimum salinity. Its water is also found spreading towards the north.

5. *North Atlantic and North Pacific intermediate water.* At the convergence in the North Atlantic, an intermediate water similar to the Antarctic region is found just south of the Labrador Sea. But it is not widespread. In the Pacific Ocean also North Pacific intermediate water is found in the north-eastern part of the Pacific Ocean, near about 40° N. The water mass loses its characteristic while moving towards west and south due to sub-surface mixing. The water mass is poor in oxygen and has low temperature.

Chapter 11 | DYNAMICS OF OCEAN WATER

The sea has great mobility and responds readily to any force acting upon it. The sea water has various types of motions, e.g. that which brings about transport of water mass in a definite direction and the other which brings about oscillation of the surface water in which rise and fall of the sea surface is more predominant than the actual forward motion of the individual water particle.

Various motions and their mechanisms come under the domain of Dynamical Oceanography which deals with the fundamental principles of Dynamics, Thermodynamics, Statics and Kinetics etc. and helps in finding out the causes of the various movements of ocean water.

SEA MOVEMENT RECORDING INSTRUMENTS

Self-recording instruments and devices have been adopted most recently to record the nature and type of sea movements. Previously rough estimates about the different motions of sea water were the only recourse. To make observations and record data about different movements, oceanographic vessels are anchored in deep water for a short or a long period as the case may be. But the first necessary condition is a fixed point of suspension which is not possible in the oceans due to greater depth. To eliminate the effect of vessels' movement, the tension on the cable is noted and at certain places records of different physical properties are taken into account to find out their general trends and intensity.

The current measurements are difficult because of the inter-mixture of so many types of movements on the sea surface. The measurements are recorded in centimetres per second or in knots (nautical miles per hour). Two types of methods, i.e., drift method and flow method, are used. The drift method in early days used logs, wreckage from vessels and glass balls as the various devices. But in order to avoid uncertainty, drift bottles were introduced and were used successfully for obtaining data over relatively large ocean areas. The flow method measures the currents by stationary instruments, past which the current flows, thus turning a propeller of some type or exerting a pressure that can be determined by various methods.

The current meters differ in design. The Ekman current meter, due to its simplicity and reliability, is widely used. But for deep sea work Ekman constructed a more complicated Repeating current meter. C. A. Johnson at the Scripps Institution of Oceanography further improved it by adding a modified suspension so that several instruments can be attached to the same wire. The whole instrument consists of a

propeller, the compass box and the vane. The propeller can be released and stopped by the messenger.

Other types of meters are Carruthers Residual meter (devised by Thorade in 1933 which is designed for giving the residual current over a long period of time), Bohnecke Mechanical Recording current meter, Witting Electrical Recording current meter, Pettersson Photographic Recording current meter and Buchanan-Wollaston Mechanical Recording current meter. Further, for tides, mechanical tide predictors have been constructed (first of its kind was made by Lord Kelvin in 1872) to record and to predict about the tides and their forces.

WAVES

The most noticeable and easily recognisable manifestation of the restlessness of the sea is in the form of waves. Waves and their study have recently become a subject of serious study. Cornish (1912-1934), Krummel (1911), and Marmer (1932) have put forward the concepts of hydrodynamics of waves. However, there is still much to be learnt about the waves, their physical character and effect on human affairs.

Waves are of various types because of the various causes responsible for their origin, as for example, there are tidal waves, seismic sea waves and wind or storm waves. But here we are mainly concerned with wind waves and their nature, characteristics and effects.

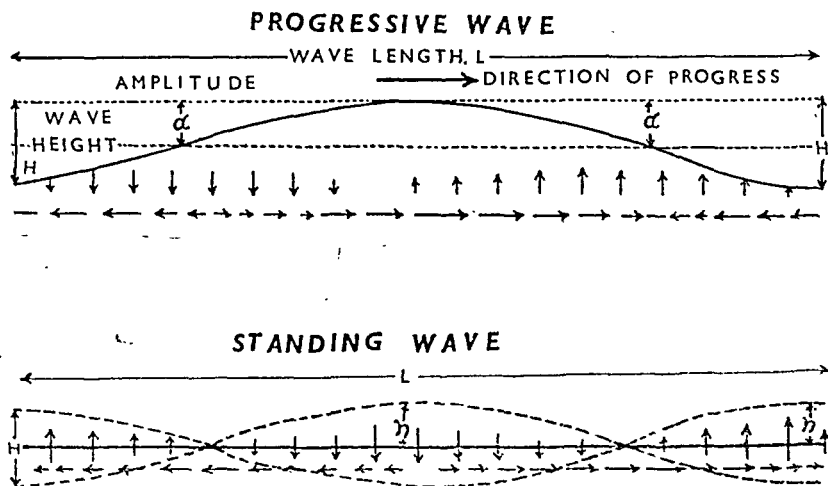


Fig. 66. Schematic representation of a progressive and of a standing wave.

(By permission of the publisher, from H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans: Their Physics, Chemistry and General Biology*. (C) 1942 Prentice-Hall, Inc., U. S. A.)

Nature and physical characteristics. The sea water in the waves simply rises and falls with a slight to and fro motion of a rhythmic character, but it does not move ahead unless winds help in the forward movement of the water in the form of current. The movements of water particles in the waves can very well be visualised by

throwing a cork. The motion of the cork will reveal the nature of wave motion. It bobs up and down according to the crest or trough of the wave. The cork moves forward when it is on the crest of the wave but comes back when it is on the trough and follows a certain form or arrangement.

The anatomy of sea waves needs explanation before we discuss about their origin, characteristics and nature. The crest of the waves is defined as its highest part and the trough is the lowest part, whereas the wave height or amplitude is the vertical distance from trough to crest. The wave length is the horizontal distance from crest to crest. The wave velocity is equal to the distance travelled by the wave in seconds and the wave period is the time taken in a fixed locality between the occurrence of one wave crest and another. A standing wave is composed of two progressive waves moving in opposite directions. It consists of a series of S-shaped (sinusoidal) undulations as shown in Fig. 66. In reality the wind-driven wave is of 'Trochoid shape'.¹ A trochoid is the path followed by a point on the slope of a wheel between the hub and the rim. The motion of the particle in a wave is forward at the crest and backward in the trough. At the middle of the hinder slope, the movement is downward and at the front slope it is upward. The motion of water particles decreases with the increasing depth of the water body. So the winds have very little effect excepting near the surface. It is calculated that at a depth equal to the length of the wave, the extent of the movement is only about 1/500 of the extent found at the surface.

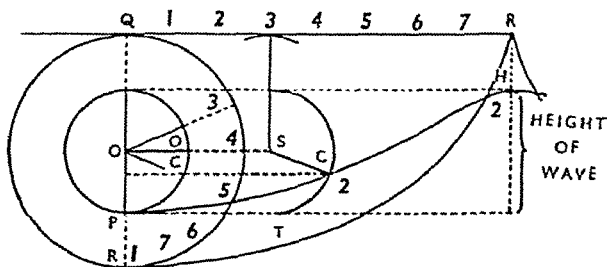


Fig. 67 A Trochoid Wave.

(By permission from, *A Textbook of Oceanography*, by J. T. Jenkins. Copyright. Constable and Company Ltd., London, W. C. 2).

The waves make a confused pattern over the sea surface due to the mixture of countless different waves of different speed, direction and intensity. In spite of this, due to a study of various aspects of waves, a theory of wave motion can be put forward which maintains or shows a relationship between the length of the wave, its velocity and the depth of the water. For fuller development of the wave the duration of wind, its sweep or the fetch and the strength of wind are the most important factors besides the depth of water. Based on the above variables, the theory of wave motion explains the differential behaviour of waves.

¹ Jenkins, J. T., *A Textbook of Oceanography*, p. 106.

Jenkins explains the movement and behaviour of waves in the deep sea water with the help of the diagram showing the trochoid curve (Fig. 67). In this diagram, presupposing that in the deep sea wave the energy is transferred and not the mass of water, the circle having the radius OQ rolls along QR , a straight line which is equal to half the circumference of this circle. This line is divided into equal parts as the circle rolls onward and the points with corresponding numbers come into contact successively. Now take a point P on the radius OR_1 of the rolling circle. As the circle rolls, point P will trace a trochoid curve marked as PC_2H representing the theoretical profile from trough to the crest. Any point on the trochoid (as the rolling circle advances) on its circumference (say 3) will come into contact with the corresponding number on the line QR . The centres of the circles must at that instant (S) be vertically below the point of contact (3), and the angle through which the circular disc and the tracing arm QP have both turned is $QO3$. But the angle POC on the original position of the circles is equal to $QO3$; consequently from S draw SC_2 parallel to OC , and make SC_2 equal to OC ; then C_2 is a point on the trochoid. Further, the tracing arm OP , for wave motion, may have any value not greater than the radius of the rolling circle OQ . If $OP=OQ$, the tracing point lies on the circumference of the rolling circle and the curve traced is a cycloid which corresponds to a wave on the point of breaking. The curve RTR is a cycloid. The crest is a sharp line or ridge (at R) while the trough is a very flat curve. All deep sea waves have this trochoid profile.

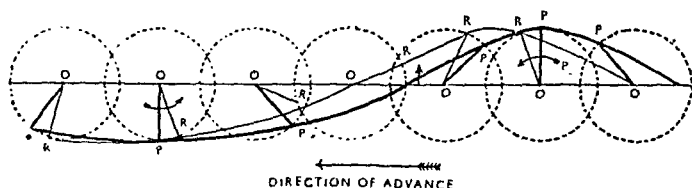


Fig. 68. The advance of a wave.

(By permission from, *A Textbook of Oceanography*, by J. T. Jenkins.
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Fig. 68 based on trochoidal theory of wave motion shows the advance of the wave, which is more rapid than the individual particles. The particles on the ridge or on the crest move forward in the same direction as the advance of the wave, while on the trough it is reverse. In the diagram, the circles are representing the position at successive eighth of a whole revolution of the wave and the particles on the upper surface are represented by points PPP and OP , OP etc. are the radii of the orbits of the wave. For the accomplishment of one-eighth of the revolution, the points P occupy the position R and RRR will be a trochoid identical in form with PPP but with its crest and hollow farther to the left. The diameters of the orbits limit the motion of the particles in the direction of the wave advance and hence they move to and fro about the centres of the orbits.

The trochoidal concept of waves further explains the effect of depth on the wave height and its forward movement. The latter decreases in a geometrical progression, whereas the depth increases in arithmetical progression. The rule is: The orbits and velocities of the particles of water are diminished by one-half for each additional depth below the mid height of the surface wave equal to one-ninth of a wave length...i.e.¹

Depth in fractions of a wave-length below the mid-height of the surface wave	0	1/9	2/9	3/9	4/9	5/9	8/9 etc.
Proportionate velocities and diameters	1	1/2	1/4	1/8	1/16	1/32	1/256 etc.

In support of the above theory, examples can be cited, viz., at 10 m depth, the height of the sub-surface trochoid would be 1.5 metres; at 20 m it is 0.75 m; at 50 m it is 9 cm; at 100 m it is 3 mm; and a storm wave of 600 feet long and 40 feet height would be 5 feet at the depth of 200 feet and only 7 or 8 inches at the depth of 400 feet.

Further, the period, speed and length of the wave are related to one another and the following formulae have been worked out:

Wave speed in knots = 3.1 times the period in seconds.

Length in feet = 5.1 times the square of the period in seconds.

Table 1² showing the relationship between these variables of period, speed and length of the waves, further elucidates the above formulae.

TABLE 1

Period in seconds	Speed in knots	Length in feet
1	3.1	5.1
5	15.5	127.5
10	31.0	510
15	46.5	1150
20	62.0	2010
22.5	about 70	about 2600

It is evident that the surface waves are mostly created by winds and there is an intimate relationship between the speed and fetch of the wind and the height and the advance of the waves on the sea surface. So in different oceans and water bodies the period, speed and length of the wave are of varying magnitude, partly due to the variations of wind and partly due to some other factors. Table 2³ illustrates the above variations of wave. The greater wave period is accompanied with

¹ Jenkins, *A Textbook of Oceanography*, p. 108.

² Colman, *The Sea and Its Mysteries*, p. 70.

³ Sverdrup, Johnson and Fleming, *The Oceans*, p. 526, Table 68.

TABLE 2
Observations Regarding Surface Waves

Regions	Wave velocity m/sec.	Wave length m.	Wave period sec.
Atlantic Ocean, Trade wind region	11.2	65	5.8
Indian Ocean, Trade wind region	12.6	96	7.6
South Atlantic Ocean, West Wind Region	14.0	133	9.5
Indian Ocean, West Wind Region	15.0	114	7.6
China Sea	11.4	79	6.9
Western Pacific Ocean	12.4	102	8.2

longer wave length and generally with greater speed as may be seen in the case of west wind region of the South Atlantic Ocean where wave period of 9.5 seconds is accompanied with the wave length of 133 m and the velocity of 14.0 m/sec., whereas in the trade wind regions of the Atlantic Ocean, the wave period of 5.8 sec. has 65 m. wave length and 11.2 m/sec wave velocity.

Wind and height of the wave. The relation between the wind and the wave is not a simple one, since so many other factors are also involved. Wind itself acts in many ways to help the formation of waves. The relation between wind direction and energy of wave may be elucidated in the following cases:

(a) When waves advance in the direction of the wind, with a speed lesser than that of the wind, there is an increase of pressure on windward side of each crest and decrease on leeward side. Here wind pressure is positive in order to increase the energy of waves.

(b) When waves advance in the direction opposite to the wind, the atmospheric pressure is negative in its action for wave energy.

(c) If the speed is greater than that of the wind and waves are moving in the same direction, then the wave energy will have negative effect due to atmospheric pressure.

In addition to the actions specified above, wind also works on the water surface by exerting a tangential frictional stress. The fetch of the wind acting upon the water is also responsible for the increased energy and consequent increase in the height of waves. Thomas Stevenson, working on the fetch, concluded that the height of waves in feet is $1\frac{1}{2}$ times the square root of the fetch in nautical miles. This formula is: $h=1.5\sqrt{f}$. Here h stands for height of wave in feet and f for fetch in nautical miles. Based on the above formula, the height of the wave at given distances from the coast may be as follows: At 10 miles, 5 feet high; 20 miles, 7 feet; 50 miles, 11 feet; 100 miles, 15 feet; 400 miles, 30 feet, and 1000 miles, 47 feet high.

Similarly, the height of waves is also related to velocity. It is equal to the velocity of the wind in miles per hour divided by 2.05. The greatest wave heights observed in oceans are about 12 m though in February 1933, U. S. S. Ramapo while proceeding from Manila to San Diego encountered the waves having height of 112 feet. This is rarely seen on the sea water as the greatest possible height of storm waves does not go beyond 60 feet. During a storm in the Bay of Biscay in December 1911, Cornish noted waves up to 12 m height. Similarly, in the North Atlantic in December 1922 'Majestic' reported waves up to 30 m.

Further, conclusions regarding the height of the waves can be drawn by the consideration of the energy of the wave. The energy of the wave is transmitted by the wind which may be termed as kinetic energy and the waves will increase in height as their energy increases. That is, greater the absorption of energy, longer and higher will be the wave. The waves of shorter length will reach their maximum height rapidly, whereas longer waves will take a long time. Further, it is also observed that at a given wind velocity, longest possible waves will be those that travel at velocity somewhat lower than the wind velocity, and the greatest wave velocity cannot exceed the velocity of the wind which created the waves.

Destructive waves. The occasional waves causing enormous damage to the invaded area are often designated as 'tidal waves' but their origin is not related to the tide-generating forces. Other agencies connected with the internal structure of the earth or the atmosphere are actually responsible for them. There are two types of destructive waves: seismic sea-wave and wind or storm-wave.

Seismic waves. These waves owe their existence to the earthquakes and volcanic eruptions in the sea. They attain tremendous dimensions with great force and fury. They are of two types: (i) sound waves due to the longitudinal oscillations produced by submarine earthquakes, and (ii) the dislocation waves or "tsunamis", born in the trenches of the ocean floor due to submarine dislocations caused by earthquake and eruptions.

The waves due to the longitudinal oscillations occur in the area of frequent earthquakes. These generally give shocks of severe nature to the sailing vessels. The second type of seismic waves proceed in the manner of gravitational waves and are very powerful and destructive in the coastal areas. History provides many examples of such seismic waves which have caused appalling loss of life. The earliest records account for the destruction of Helice in Corinthian Gulf in 373 B.C, and of Alexandria on the eastern coast of Mediterranean in 358 A. D. More recently, the records of the Lisbon earthquake of 1755 show a tremendous loss of life and property due to a 50 feet higher wave than the highest tide level at Cadiz. The same wave reached the West Indies in $9\frac{1}{2}$ hours and there caused loss of life and property. In Japan, similar waves on many occasions brought great destruction and loss of life, for example, the case of Awa floods in 1703 in which 100,000 persons lost their lives. The eruption of the volcano Krakatau in the Sunda Strait on August 26, 27, 1883 caused tremendous loss of life and property and created havoc.

Sometimes these tidal waves, due to the earthquakes, travel long distances and affect the coastal areas of distant countries. On 1st April, 1946, on the coast of Hawaiian islands, the waves affected the area after travelling 2000 miles from the deep trench off the island of Unimak in the Aleutian area. The seismic waves originated due to the eruption of Krakatau, travelled through the Pacific and affected the western coast of U. S. A. after covering a distance of 10,000 miles. Very recently, in 1960, the sea waves, due to seismic disturbances in the Chilean waters, caused great havoc on the coasts of Japan, after travelling thousands of miles.

The waves of seismic origin behave like the long gravitational waves and so their velocity of progress is calculated according to the $\sqrt{gh}$, when the depth is assumed uniform over the bottom. Due to the variable of the depth of the bottom being added, the velocity becomes $\sqrt{ghm}$ where hm is the average depth. Further, according to the studies of Krummel (1911) and Gutenberg (1939), the length of the period of tsunamis varies between 15 and 60 minutes. After knowing the period length (the velocity), we can easily find out the wave length. For instance, for a depth of 200m, the velocity of the progress will be $\sqrt{gh} = 44.2$ m/sec. The wave length with a period length of 30 minutes will be 79.5 km. Thus we can say that these waves behave in a manner similar to the long gravitational waves.

Wind or storm waves. The waves of the oceans, due to the inundations over the surface of the oceans caused by the storms and strong winds are the elements of destruction and havoc on the coastal lands. Due to a rise of the general water level, a storm tide attacks on the coastal lands mostly in hurricane zones. The most notable disasters were those on the coast of Galveston, Texas, on 8th September, 1900; on the coast of Newfoundland on 21st September, 1938; and in the Bay of Bengal on 7th October 1937 (when 20,000 boats were destroyed and 300,000 people were drowned).

The great waves called 'rollers' rise periodically on certain coasts lasting for several days but they are related to the changes in barometric pressure over the ocean several thousand miles away from the affected area.

Chapter 12 TIDES

Tides and tidal waves are the most important among various types of motions in the sea. The tides affect the ocean water to the deepest part of the basin, sparing not a single drop of water. They act in response to the mysterious force of the attraction of moon. The universality of tides may be put in the words of the Venerable Bede: "In every country the moon keeps ever the rule of alliance with the sea which it once for all has agreed upon."

The waves produced by tidal movement are the longest ones known in the ocean. The tide wave occurs in the rhythmic rise and fall of water in response to the effects of oscillating forces such as those produced by the varying gravitation of the moon and the sun. In the words of H. A. Marmer "twice each day, in rhythmic fashion, it (the tide) rises and falls in response to the mighty pulse of the tide producing forces. These stir the sea to its depths and bring about the phenomena which for short are called the tide, whose extent of the rise and fall at any place is not constant but varies from day to day." The tides are actually more complicated and present a striking paradox. As though the force of motion is cosmic which presumably acts impartially on all parts of the globe, but the nature of tide and its range is a matter of local characteristics.

The universality and everyday occurrence of tides has been a matter of interesting study since the earliest times. There exists an enormous literature dealing with this phenomenon, partly in the form of theoretical studies, observations and discussions, and partly in the form of popular treatises.

The observations and studies of tides in the classical period of world history were very scanty and sketchy due to the fact that the classical world was around the Mediterranean Sea where the tides were least impressive. The records of the Greeks, the Romans, and the Biblical literature tell little about tides. The earliest reference appeared in the writings of Greek historian Herodotus. As early as 325 B. C. Pytheas of Massila who crossed the Atlantic Ocean up to the British Isles noted the relationship existing between the tides and moon. Previous to this the statements regarding tides were fanciful and philosophical. Later on, by the time of Pliny's *Historia Naturalis* (77 A. D.) reasonable knowledge of the tide was developed and the fact that the tide is due to the combined action of the sun and the moon and that the moon plays the leading role was established.

Further, from the classical times to the early medieval period the knowledge about the phenomena of tides became more intensive. In the

8th century, the Venerable Bede wrote a treatise with the caption 'On the bond between the sea and the moon.' In the 13th century an Arabic author Zakriyya ibn Muhammad ibn Mahmud al Qazirm gave a physical explanation of the action of the sun and the moon which created tides.

In 1687, Isaac Newton for the first time gave a rational explanation of tides and tide producing forces of the moon and the sun. He proved that two bodies attract each other with a force directly proportional to their masses and inversely proportional to the square of distance between them. Thus he propounded the theory of equilibrium. Further, as a result of the proposal of the Academy of Sciences at Paris, in 1738, four prominent persons (Daniel Bernoulli, professor of Anatomy and Botany at Basel; Colin Maclaurin, professor of Mathematics at Edinburgh; Leonard Euler; and Antoine Cavalleri) wrote essays on the laws of tides and tidal movements. Later on, a French mathematician and astronomer Laplace based ideas on the then available knowledge of tides and gave the dynamic theory of the tides. A different approach in 1842 was made by the English mathematician astronomer Airy by treating the tides as a result of movement of waves in canals. Later on, with the advent of the 20th century, Ferrel and Harris in America; Kelvin, G. H. Darwin, Lamb and Hough in Great Britain; Levy and Poincare in France and Krummel (1911) and Marmer (1932) added to the further development of the science of tides. The knowledge of the geographic distribution and local peculiarities of the tides has increased enormously.

TIDE PRODUCING FORCES

The tide is a phenomenon of the sea in response to the pull of the moon and the more distant sun. The character of tides is complicated because of the varying positions of the attracting bodies. Hence it is necessary to account for these forces separately as well as in co-ordination. It was put forth by Newton that there is a force of gravitation between every drop of sea water and even the outermost star of the universe—though the pull of the outermost star is so slight as to be obliterated. In this theory of universal gravitation, the force of attraction is directly proportional to the product of the masses and inversely proportional to the square of the distances between them.

The gravitational attraction of the moon is felt at the surface of the earth because of nearness to the earth as compared to other planets and stars. The mass of moon in Fig. 69 is represented by M and the earth by units. The distance between the earth's centre and moon's centre is r . Thus the gravitational force is equal to m/r^2 . At the same time another force which is directed away from the moon is a centrifugal force working to the magnitude of m/r^2 . The attraction of the moon is felt on the line joining the two centres of the earth and the moon. But moon's attractive force is not equal on all the places on the line. As the diameter of the earth is 8000 miles, hence the surface of the earth is 4000 miles nearer to the moon. Similarly, the exactly opposite part of the earth on the same line will be 8000 miles further away from the moon. The centre of the moon is 240,000 miles from the centre of the earth and 236,000 miles from its nearer side. Thus the attraction at the surface of the earth would be greater as compared to the attraction at the centre due

to the nearness. As liquid is easily attracted in comparison to solid, so the ocean water rises under the moon and forms the tide.

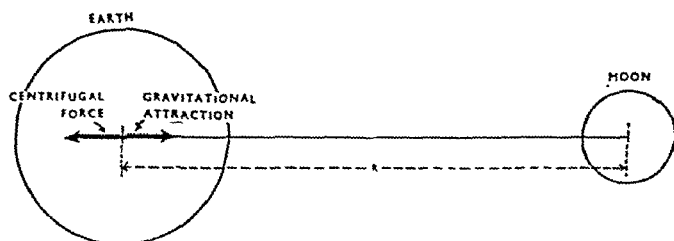
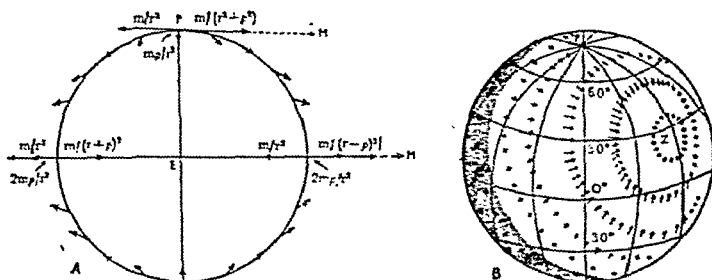


Fig. 69. (A) Schematic representation of the gravitational attraction between the earth and the moon and the centrifugal force which balances the attraction.



(B) Schematic representation of the tide-producing forces in a plane through the line joining the centres of the earth and the moon (left). Distribution of horizontal tide-producing forces over the earth (according to G. H. Darwin). The moon is at zenith above the point marked Z (right).

(By permission of the publisher, from H. U. Sverdrup, M. W. Johnson, R. H. Fleming, *The Oceans: Their Physics, Chemistry and Biology*. (C) 1942. Prentice-Hall, Inc., U. S. A.)

Same phenomenon is found on the other side also. If p is the radius of the earth the attraction at surface would be $m/(r-p)^2$ because the centrifugal force remains almost the same at the centre or at the surface; difference between the centrifugal and gravitational forces at the surface is not equal but would be $m/(r-p)^2 - m/r^2$, which is numerically equal to $60.34 p$. At this point the third force, that is attraction of the earth, also comes up to make the net force of moon equal to $2mp^3/r^2 = 1.176 \times 10^{-7}$. Similarly, at a point opposite to the moon on the earth, where attraction is less than the centrifugal force, the net force of the moon is proportional to $m/(r+p)^2$. The disturbing force is again found from the difference and is equal to

$$\frac{m}{(r+p)^2} - \frac{m}{r^2} = -2m \frac{p}{r^3}$$

where the minus sign indicates that the force is directed away from the moon and so the disturbing force (attraction of the earth) is of the same

magnitude as it is on the first point. Hence it reduces the acceleration of gravity by $0.000115 \text{ cm/sec}^2$ at each point. Now take a point at the surface of the earth at right angles to the line joining the centres of the moon and the earth, where the disturbing force in spite of reduction increases the acceleration of gravity by 0.00058 cm/sec^2 . Further, for a point on the earth surface, the disturbing force has a vertical and horizontal component. So the equations¹ of vertical and horizontal components of the disturbing forces are:

$$\text{Vertical component: } 3m \frac{p}{r^3} (\cos^2 \theta - 1/3)$$

$$\text{Horizontal component: } 3m \frac{p}{r^3} \sin \theta \cos \theta.$$

where θ is the angle between the line joining the two centres and the line from the centre of the earth to the point on the earth's surface.

Thus the actual tide producing force is the difference between moon's attractive forces at the surface and the centre of the earth, that is $m/(r-p)^2 - m/r^2$ or to the proportion of $1/30\text{th}$ when the two forces are 31 and 30.

The similar case of attractive force producing tide is found with the sun, though there is a difference in values. The distance between the sun and the earth surface and the centre is 93,000,000 and 92,996,000 miles respectively. The attractive forces are $93,000,000^2$ and $92,996,000^2$, or in proportion to 1,000,086 and 1,000,000. Hence the tide producing force at the centre is $86/1,000,000\text{th}$ of the attractive force of the sun. Further, the mass of the sun is 25,500,000 times of the moon but due to its greater distance, its attractive force at earth's centre is only 169 times of the moon. Its tide producing force is $86 \times 169/1,000,000$ of the moon's attractive force at the centre, i.e. $4/9\text{th}$ of the tide producing force of the moon. Jenkins has calculated that the strength of the tide producing forces of moon and sun have a ratio of 11:5. The height of the tide due to the moon is about 356 millimetres and that due to sun is 164 millimetres.

The question regarding the possibilities of other heavenly bodies to produce tides is not important for the earth due to their greater distance. On the basis of 70 times greater volume and 100 times greater distance of Venus, the tide producing force as compared to that of moon is $70/100 \times 100 \times 100$. Thus the Venusian tide must be $1/10\text{th}$ of an inch in comparison with that of the moon's having a range of 100 feet. Similar calculations as regards Jupiter may be drawn, that is, Jupiter's tide producing force is less than $1/1,00,000\text{th}$ of the moon, and is $26,000/1500 \times 1500 \times 1500$. So among all the heavenly bodies, the sun and moon are the only forces which account for the rise and fall of tides on our earth.

¹ *Ibid.*, p. 547.

Distribution of tide producing forces on the earth's surface.

The general distribution of the tide producing forces would have almost caused a vertical uplift of water at the moon's meridian (below moon) but on the same longitude north and south of this, the intensity and the direction of tidal force would be different. It would, however, result in a longitudinal component and the general movement of water would not be vertical towards the moon's meridian.

The tide producing forces vary according to the changing positions of the celestial bodies in relation to one another. Therefore, the time of tide and the tidal elevations at any place on the earth's surface vary accordingly. Due to the varying positions of bodies, the nature of tides becomes more complicated.

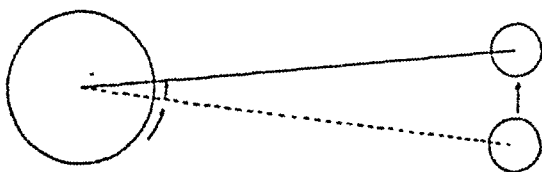


Fig. 70 (A). The daily change in the time of high tide.

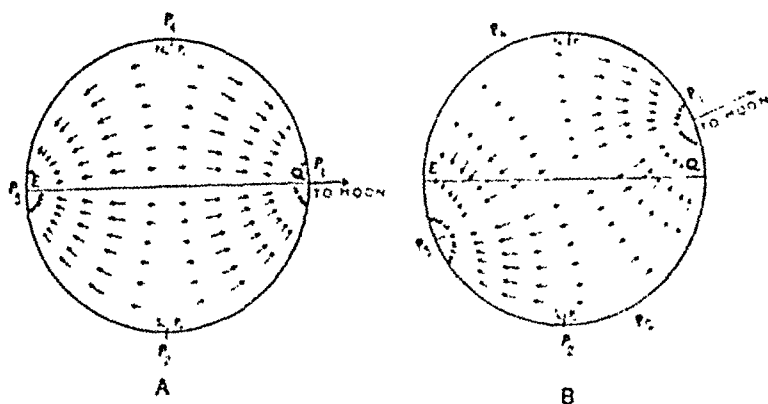


Fig. 70 (B). Distribution of tidal forces. Moon (A) on Equator, and (B) north of Equator.

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Lunar force and the changing position of moon. Due to the factor of distance, the intensity of the tidal force is greater at the point just below the moon than on the other points on the earth's surface. Hence p^1 will experience a maximum pull, resulting in the tide. At the same time at p^2 the point just opposite to p^1 will also

have a tide due to reasons that will be explained later on. As p^2 and p^4 will be further away from the moon's attraction, the height of the tide will be less. Therefore, at the same time there are two high tides and two low tides on the surface.

Now as we know that the earth rotates in the direction from west to east, p^1 point would not remain fixed below the moon. It would move away and other points on the surface would take its place. As the earth completes its circle in 24 hours, p^2 , p^3 and p^4 points would come consecutively below the moon, after an interval of six hours. Therefore, once in a day each point comes below the moon and experiences two high and two low tides. The interval between the high tide of the previous day and the high tide of the following day (below moon) should be 24 hours. But as apart from the earth's rotation, the moon is also moving in the same direction round the centre of the gravity of the earth. In 24 hours p^1 takes a complete circle, whereas the moon also moves slightly ahead. So p^1 point on the earth's surface requires more time (about 50 minutes) to come beneath the moon on the next day as shown in Fig. 70A. Hence the total duration required to complete the two cycles of high and low tides at any place would be 24 hours 50 minutes. So each day the moon's high tide would be 50 minutes later than that on the previous day.

Hence the tides at points occupying various positions on the earth surface are due to the horizontal component of the moon's attraction and

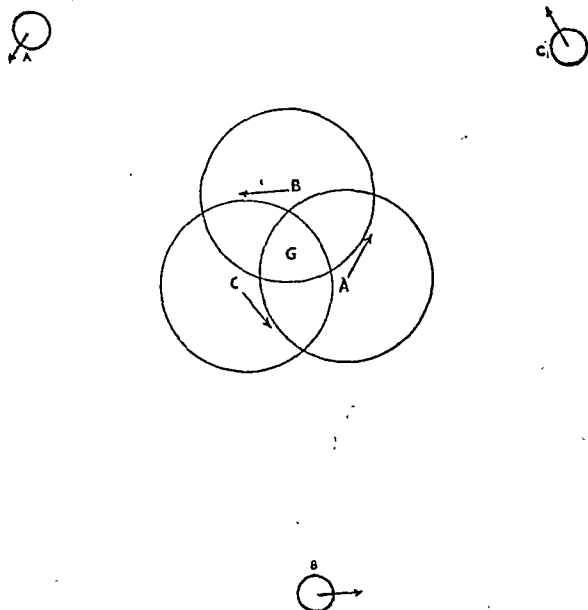


Fig. 71. The relative movements of the earth and the moon.

(By permission from, *Physical Geography*, by Phillip Lake. Copyright. The Cambridge University Press.)

due to the great mobility of water. Similarly, the tides produced by the forces of the sun at one place would repeat on the next day exactly at 24 hours instead of 24 hours and 50 minutes. So there is a difference in the time of the tide produced by sun and moon.

Tides and relative positions of sun, moon and earth. Each point on the ocean is acted upon by two forces, the sun and the moon, each tending to produce its own tide ellipsoids. As these forces act simultaneously, the tide ellipsoids present at any point are due to the combination of the above two ellipsoids. The various positions of sun, moon and earth and their results are the following:

(1) *Moon in syzygy.* When the sun, moon and earth are almost nearly in a line—the case at full moon and at new moon as shown in Fig. 72A—the bodies will be jointly exerting the pull and thus produce high or spring tides, as at this time tide ellipsoids formed by two bodies are added together.



Fig. 72 (A). Spring Tides.

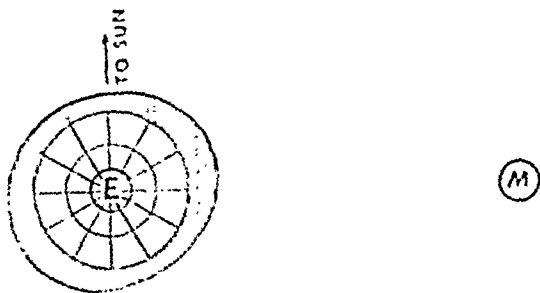


Fig. 72 (B). Neap Tides.

(2) *Moon in quadrature.* When the lines joining the three bodies are almost nearly at right angles to each other as shown in Fig. 72B., the tidal forces will be at right angles or opposite to each other and make conditions suitable for neap tides not for high as in the former case.

(3) *Effect of varying declination.* The factor of declination makes the case of the tide more complicated. The plane of the earth's equator is inclined at an angle of $23\frac{1}{2}^\circ$ to the plane of the ellipse and the plane of the moon's orbit round the earth is inclined at an angle of 5° to the plane of the ellipse. Thus the attractional forces of the moon and sun are abnormal to the surface of the sea, at a place on the equator of the earth.

When the sun is at the equinoxes it will directly be at equator having the declination of zero or so, and sometimes within a fortnight the moon will also be on the equator having the zero declination. At this time due to combined efforts of sun and moon, there will be equinoctial spring tides. But at the time of solstice in the summer and winter months, the declination of sun and moon will be maximum and so due to less direct effect they will produce ordinary spring tides.

(4) *Orbits of celestial bodies.* The moon follows the elliptical orbit round the earth and therefore sometimes when she is nearest to the earth (in perigee) the tide is higher than the normal, and sometimes when farthest from the earth (in apogee) the tide force is below normal. These periods of perigee and apogee occur twice during the lunar months. Since the tide producing force varies inversely as the cube of the distance, tides are about 20% above the average in perigee and 20% below the average in apogee. Similar conditions are found in the earth's orbit round the sun. During perihelion when earth is 91.4 million miles from the sun, the tide is higher than in aphelion when earth is 94.5 million miles from the sun. These periods occur twice in a solar year.

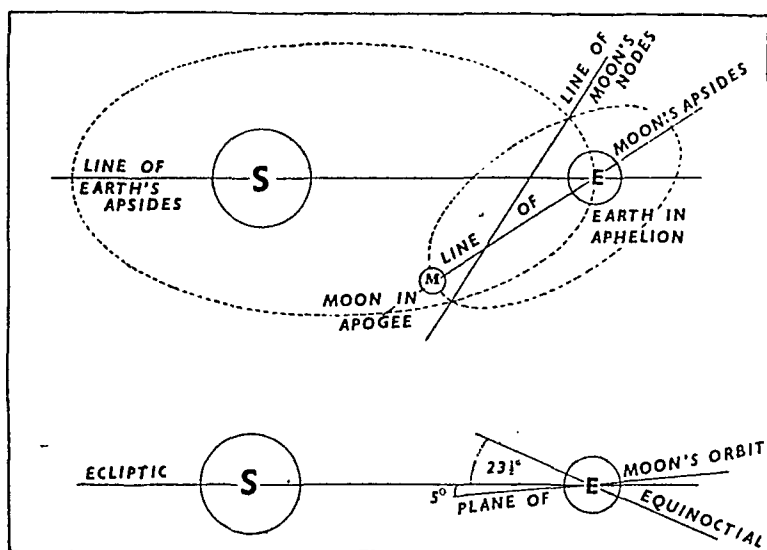


Fig. 73. Illustration of long periodic variations in the tide-generating force when the moon is in apogee and the earth in aphelion.

(5) *Long periodic variations in the tide generating force.* Besides the above variations so far described, there are longer periods of variations affecting the tidal forces. In Fig. 73 the earth's and moon's elliptical orbits have lines of apsides formed by major axes. These apsides rotate. The earth's apside moves very slowly but moon's apside rotates with a period of about 8.8 years. The planes of the two orbits intersect in a line called the line of nodes which rotates with a period of about 18.6 years. Further, as shown in Fig. 74, after an interval of about 1600 years, the positions of these bodies will be : the earth is in perihelion, the moon in perigee and

the sun and moon in conjunction or in opposition. Thus there shall be a condition of an absolute maxima in the potential of the tidal force. The dates of such absolute maxima are calculable. They occurred in 3500 B. C., 1900 B. C., 250 B. C., 1433 A. D. and the next will be in 3300 A. D.

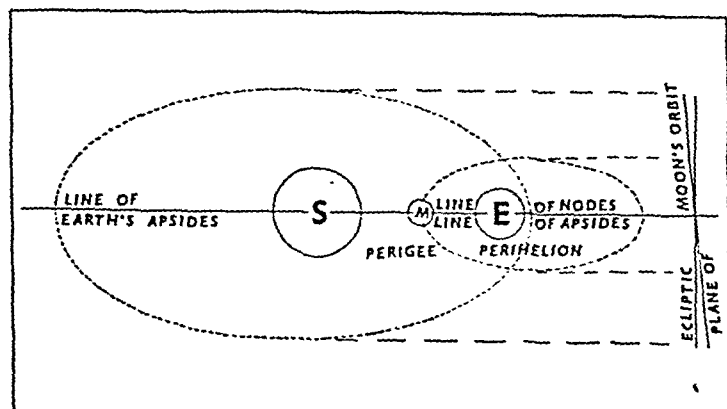


Fig. 74. Illustration of long periodic variations in the tide-generating force when the moon is in perigee and the earth in perihelion. The line of the earth's apsides, the line of the moon's apsides, and the line of nodes will coincide. This is the configuration for an absolute maximum.

(Figs. 73 and 74, by permission, from *An Introduction to Oceanography* by James Johnstone. Copyright 1923. Hodder and Stoughton Ltd., London.)

TYPES OF TIDES ✓

Tides present a striking paradox of the cosmic forces acting impartially on the sea water, and nature of the tide differs greatly within a very short geographic distance. They are not a simple phenomenon as calculated by the mathematicians. It is not the phenomenon which is completely governed by the latitude of the place. The intensity of tides does not bear any relationship to the latitude of the place; thus St. John's (Newfoundland) and Brest (France) in spite of being on the same parallel have different tidal heights. The Newfoundland tide has $1\frac{1}{2}$ to $3\frac{1}{2}$ feet of rise while at Brest it is about 15 feet. Another striking example of a complete disregard of the latitude and the longitude in the case of tides is found at the two ends of the Panama Canal. It was later found to be due to the irregular shaped basins of varying depths and the effects of friction due to which the tide does not respond immediately and equally to the variations in the position of moon, sun and earth.

The varying response of the bodies of water to the tide-producing forces of sun and moon is due to the various kinds of forces which determine the nature and type of tides. The semi-diurnal or semi-daily forces creating semidiurnal tides act in a complete circle in half a day while the daily forces do a complete circle in a day resulting in daily tides. The former is affected by rotation while the latter is due to rotation and declination

of the sun and the moon. Hence the main types of tides, as shown in Fig. 75, are the following :

- (i) Semi-diurnal tides—recur at intervals of $12\frac{1}{2}$ hours.
- (ii) Diurnal tides—recur at intervals of $24\frac{3}{4}$ hours.
- (iii) Quarter-diurnal tides—very exceptional.
- (iv) Spring tides—recur once a fortnight due to the revolution of the moon and its declination.
- (v) Neap tides—recur once a fortnight due to the revolution, declination and varying positions of the moon.
- (vi) Monthly tides—due to the revolution of the moon and its position at perigee and apogee.
- (vii) Equinoctial spring tides—recur at intervals of 6 months, due to revolution of the earth round the sun and sun's varying declination.
- (viii) Yearly tides—due to revolution of the earth and position at perihelion and aphelion.

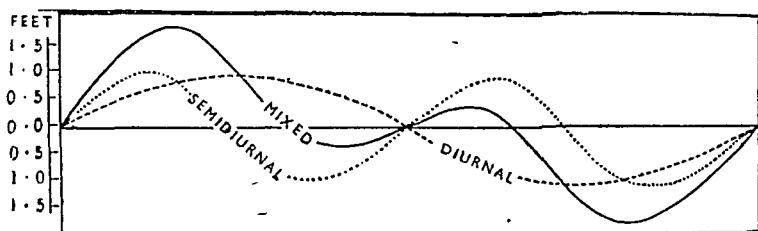


Fig. 75. Various types of tides.

The distribution of the various types of tide on the world map is given in Fig. 76 which shows the following regional pattern. There is a preponderance of semi-daily forces at the equator and their least influence at poles, whereas the daily forces show just the opposite conditions. The coastal-wise survey of the phenomenon of tides shows that the semi-diurnal tidal areas are limited to the coasts of West Bengal, West Pakistan, Burma and east coast of Africa in Indian Ocean, the east coast of U. S. A., Canada, whole of Hudson Bay, the northern coast of Venezuela, Brazil, the south-eastern coast of Argentina and whole western coast of Africa, Europe and British Isles in the Atlantic Ocean; and in Pacific Ocean this type is limited to the coasts of Samoa, Pitcairn and New Zealand Islands.

The diurnal tides occur on south-west part of Australia in Indian Ocean; in Atlantic Ocean it is over the Gulf of Mexico from Florida to Panama coast and along the southern coast of lesser Antilles in Caribbean Sea only; and in the Pacific Ocean it is in the Gulf of Siam, along the northern coast of Sumatra, Java, the southern coast of Borneo, the northern coast of New Guinea, the eastern coast of Vietnam, and the western coast of Japan in Japanese Sea.

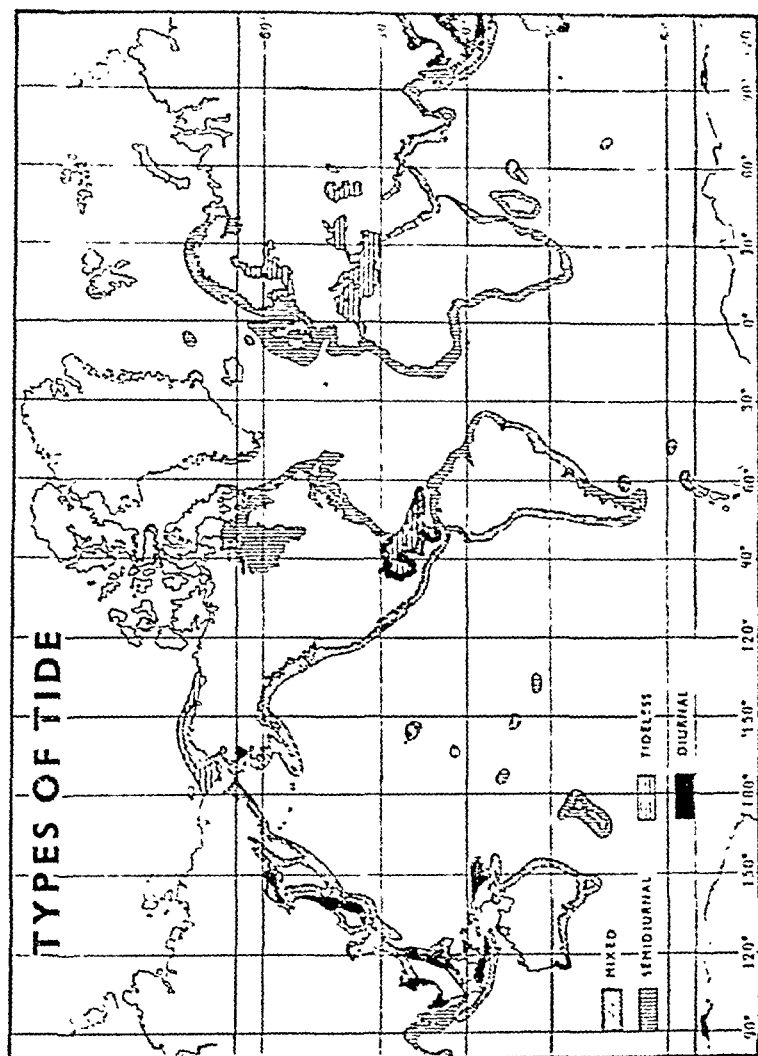


Fig. 76. Types of tides on the world map.
(By permission from *The Geographical Review*, New York, Vol. 23, 1933, p. 266).

The mixed type of tides occur in Indian Ocean along the Asian coast of Arabian Sea, coast of Ceylon, round about Mauritius islands, eastern coast of Madras and Andhra Pradesh of India, the south-western coasts of Sumatra and Java; in the Atlantic Ocean this type is limited to eastern coast of Brazil, north-eastern coast of Argentina and Falkland, S. Orkneys and S. Shetland islands areas; and in the Pacific Ocean, it is widespread over the coast of China, Korea, Manchuria, eastern coast of Japan islands, Sea of Okhotsk, Bering Sea, western coasts of

Canada, U. S. A., Mexico, Central America, Peru, Chile and over the southern and eastern coast of Australia and Hawaiian islands. Further, there are tideless areas experiencing low tides of two feet. These are northern coast of Alaska, Society Islands and Palmyra Islands in Pacific Ocean; whole of the Gulf of Mexico and Caribbean Sea beyond the coasts, the Baltic Sea, the Mediterranean and Black Sea in Atlantic Ocean and the Caspian Sea.

There seems no hard and fast line to demarcate between the mixed type of tides. The mixed tide having wide range of inequality shows three varieties based on the inequality in high, low or in both high and low tides. The example of inequality mainly in low water can be cited by taking the case of Golden Gate and its tidal features. This characteristic of having inequality in low water is further extended into Pacific coastal tides. The inequality in low water is 87% in the tropical tides and 33% in higher latitudes. The tidal curves of December 17 and 18, 1922, for Seattle, Washington, show the inequality between the two lows up to the extent of 9 feet or more.

The next feature of the mixed type of tide is marked with inequality in the high water. The example may be cited from the Atlantic coast and from the coast of Philippines where the diurnal inequality is principally marked in the high waters. The tidal curve of Honolulu for December 17 and 18, 1922, shows this feature where two highs go up to 1.5 feet and the next set of high remains only up to the sea level. So there is a range of 1.5 feet between the two highs.

Thus it can easily be interpreted that the different varieties of the mixed tide arise from the varying combinations of the daily and semi-daily tides and the analysis of such varying combinations may be achieved by the help of harmonic analysis of tidal phenomenon. Further, the vanishing tides form the connecting link between the tides of the mixed and the daily types. The vanishing tide occurs due to the equal range of inequality at the low and high tides. This fact of vanishing tide is due to two characteristics : the inequality in the highs comes up to sea level and near the height of low water, whereas the inequality in the lows comes just above sea level and near the height of high water. The tide at Port Angeles, Washington in the Strait of Juan de Fuca, on Jan. 11, 1922 illustrates this type.

In conclusion, we can put forth the two ideas about the origin of the mixed tides. According to one idea these mixed tides are due to the mixing of semi-daily and daily types of tides. Further, the second idea stresses the fact of varying ratios of mixing of the constituents of mixed types of tide. Regional examples can be obtained, viz., the tides of the Atlantic Ocean show the predominance of semi-daily constituents, the Gulf of Mexico shows the daily constituent, and the Pacific and the Indian oceans show an equal predominance of the two types.

Tidal bore and tides in rivers. The tidal bore occupies a significant position in tidal phenomenon. It is created when there is a forced entry of tidal wave against the running water of river or channel. These are directly or indirectly connected with the tides of the open sea

which bring sea water in them. So the nature and magnitude of river tides mainly depend upon the adjacent seas and their tidal phenomenon.

The tides in the rivers and estuaries are due to many factors : slope of the river, flow of water, range of tides in the adjacent seas, and the factor of friction. Since the tides in these water bodies (rivers and estuaries etc.) are directly affected by the tidal forces which are acting in the open sea, the features of river tides are considered as the wave motion in progress. According to mathematical calculations the progress of the tide should vary with the depth, the formula being $t = \sqrt{g/h}$, where t stands for the rate of progress of the tide, g for the acceleration of gravity and h for the depth of the water way. Further, the average value of the acceleration of gravity is 32.17 feet per second, so t in terms of nautical miles per hour is $3.36\sqrt{h}$.

With the progress of the tidal waves up stream, there will be some changes in the rise and fall of the tide. The tidal curve which is actually symmetrical near the mouth of the river becomes more and more asymmetrical further inside. The front i.e. the interval between low water and high water) becomes steep and the back i.e. the period between high water and the next low water becomes lengthy and gentle. It is due to too much steepening of the front that the phenomenon of tidal bore occurs. Its high water travels faster than low water. This factor may be made clear by the example of the tidal movement up the river Hudson on east coast of U. S. A., as shown in Table I.

TABLE I

Place	Distance in nautical miles from mouth	Time of high water	Time of low water in relation to mouth
Tarry town	24	1 ^h 50 ^m later	2 ^h 00 ^m later
Storm King	45	3 ^h 30 ^m „	3 ^h 59 ^m „
Albany	125	9 ^h 30 ^m „	10 ^h 30 ^m „

The phenomenon of Bore occurs in a number of waterways and examples may be cited here in order to show its intensity, magnitude and duration. The Amazon is remarkable for the phenomenon of Bore occurring for 200 miles upstream in the river. In reality as many as 5 tides travel upward at a time due to this long distance. One of the largest bores occurs in the Tsientsang river which flows into the China Sea. The cause behind this bore is the funnel-shaped waterway narrowing considerably and the presence of extensive shoals and mud banks in the river. The continuous silting of the river bed from the past made it more enormous and dangerous. It is the largest and most dangerous bore, though shipping is controlled by it. During most of the month, the bore advances up the river in a wave 8 to 11 feet high moving at a speed of 12 to 13 knots. Its front is "a sloping cascade of bubbling form, falling forward and pounding on itself and on the river." Sometimes during the spring tide at new and full moon its front rises up to 25 feet, forming a high advancing wall.

The phenomenon of Bore has been best studied in the Bay of Fundy by Dr. Dawson, Superintendent of the Canadian Tidal and Current Survey. In the Bay of Fundy, the bore at Moncton on New Brunswicks Petitcodic river, is the most impressive at the spring tides when a width of half a mile is formed by the advancing water up the stream. Here the bore arrives midway between low and high water or three hours before the high water. Further examples may be gathered from different regions of the world, e.g., Colorado river at the head of the Gulf of California, Brazilian rivers and Turnagain Arm in Cook Inlet, Alaska etc.

Tidal Streams. The vertical rise and fall is accompanied with the horizontal movement of the water under the impact of tide-producing forces. This horizontal movement of water is known as tidal stream or tidal current. These two movements—rise and fall and the horizontal movement—are intimately associated with each other and their relationship is determined by the configuration of land and the depth of water bodies. These tidal currents represent the motion of water where the velocity reaches its maximum in the direction of progress at high tide and in the opposite direction at the time of low tide. Table 2¹ shows the velocity of tidal currents and maximum horizontal displacement in a wave of amplitude 100 cm proceeding in water of constant depth (earth's rotation and friction neglected).

TABLE 2

Semidiurnal tide		Depth (m)				
		100	500	1000	2000	4000
Maximum	{ cm/sec.	31.3	14.0	9.9	7.0	4.9
Current	{ knots.	0.61	0.27	0.19	0.14	0.10
Maximum	{ km.	4.4	2.0	1.4	1.0	0.7
displacement	{ nautical miles	2.4	1.1	0.75	0.54	0.38

¹ Sverdrup and others, *Oceans*, p. 566.

The table also shows the horizontal displacement and the velocity of currents. If to this is also added the factor of friction and earth's rotation, then the magnitude of displacement will be more with the increase in velocity.

Further, the configuration of the water bodies also affects tidal current in its magnitude and direction. The variation in the width of water bodies also leads to modifications in tidal currents. The factors of having more than a single standing or progressive wave also affects the direction and velocity of the tidal currents.

The tidal currents and streams and the tides, though representing two aspects of the same phenomenon, are closely inter-related. The character of tidal currents is closely governed by the character of tides and the periods of tidal current are in agreement with the periods of tides. Take the case of the Atlantic where the nature of the tide is of semi-diurnal type, so the nature and character of tidal currents is also of semi-diurnal type. Similarly, on the Pacific coast of U. S. A., the tides are of mixed type having a large range of diurnal inequalities; thus the tidal currents also exhibit the same pattern of mixed type.

Off-shore tidal currents. The tidal currents further towards the deep and open water of the sea are termed as the offshore tidal currents. They behave unlike the tidal currents of the rivers, gulfs, bays and estuaries. These offshore currents are rotary, as opposed to rectilinear currents. The latter have distinct periods of flood and ebb, though the direction is constant and the transition between ebb and flood is marked by the slack water. These characteristics are found in the tidal currents of the rivers, bays and gulfs. But change in the direction of offshore rotary

TABLE 3

*Current observations at Nantucket Shoals Light Vessel,
September 24, 1919*

Time P. M.	Currents	
	Velocity	Direction
Noon	1.1	N 79° E
1	1.0	S 45° E
2	1.0	S 2° E
3	1.1	S 32° W
4	1.3	S 43° W
5	1.3	S 55° W
6	1.2	S 77° W
7	0.8	N 47° W
8	1.0	N 24° W
9	1.0	N 13° W
10	1.2	N 2° W
11	1.2	N 43° W
Mid-night	1.0	N 63° E

current is constantly occurring. Due to so many difficulties of making observations at offshore sea, the deductions about the nature, characteristics and magnitude of offshore tidal currents are often faulty.

The above conclusions may be attested by the observations made in Nantucket shoals on 24th September, 1919, as given in Table 3¹. It shows that the velocity of the current is almost constant but a progressive change at each hourly observation in the direction is marked. Further, on these tidal currents the effect of depth does not seem to be a modifying force, as the observations made on Nantucket Shoals Light Vessel at 100 feet show exactly the same characteristics as the current has near the surface. Hence the velocity and direction of the tidal current (except in shallow waters) from surface to the bottom are practically the same. Further, the rotary current occurring in the offshore tidal currents exhibits all the variations with respect to changes in moon's position. So, the offshore currents on the Pacific coast show greater diurnal inequality (a characteristic of the mixed type of tides in the Pacific Ocean) in comparison to the offshore currents on the Atlantic coasts. The rotary offshore tidal currents are further modified and controlled by an interaction of tidal movements of varying directions.

Earth history and changing tides. The changing phase of earth history is marked with the varying degree of intensity of tides and tidal forces. A general statement may be put that "Tides reach their greatest grandeur and power in the younger days of earth and that they slowly grew feebler and less imposing, until one day they ceased to be." The moon, which is the outcome of the tearing away of the outer crust of the earth, must have been close to the earth in the early days of our planet. The present position is due to the gradual pushing away for the last 2 billion years. When the moon was at its half distance as compared to the present, the tides must have been several hundred feet high due to the great force of the moon. The tides must have been eight times higher as compared to their present magnitude. The fury of tides must have been very great and the tidal waves must have been very strong to erode the inner and distant parts of the continents. On the other hand, this tidal friction gradually resulted in slowing down of the earth's rotation, requiring 24 hours to complete it. This gradual retardation in earth's rotation resulted into the more feeble tides day by day. According to mathematical calculations due to this retardation of earth's rotation, the day will be about 50 times as long as it is now. This lengthening of the day will result into the lesser intensity of tides and tidal forces. This tidal friction is pushing away the moon from the earth which will, according to the law of gravity, reduce the strength of the tidal force of the moon. Ultimately, the time will come when the length of the day and the month will be equal and hence there will be no lunar tides because the moon will not rotate relatively to the earth.

THEORIES OF TIDES

Various theories are advanced to explain the origin of the tides. They are based on the synthetical approach to the observations made in various oceans. The tidal theories involve difficult mathematical deductions and analysis. The first mathematical theory which states the response

¹ Marmer, *Tides*, p. 116.

of the ocean to the tidal forces was given by Newton in 1687. Newton's approach made the foundation on which subsequently the later works are based. We give below some of the important theories.

The Equilibrium Theory. Isaac Newton in 1687 in his *Principia* developed the theory of equilibrium in which he assumed a mass of equilibrium under the combined forces of gravitation of the celestial bodies. The earth, the moon and the sun are all in equilibrium due to their respective pulls towards each other. As moon is nearer to the earth in respect to the sun, its gravitational force is felt more on the earth. In response to the gravitational attraction of the moon and the distant sun, the liquid sea is heaped up just below the moon and the phenomenon of tide results. Similar tides do result by sun's attraction but their amplitude is too small.

It is observed that at one time there are two tides on the earth: one is just below the moon which may be attributed to its attraction, and the other is just on the opposite side of the moon's meridian. The latter one is attributed to the fact that due to the attraction of moon the solid earth also moves slightly towards it with the result that oceanic waters are left behind and a bulge is created there. Later, it was stressed that the earth and the moon while attracting each other revolve around their common centre of gravity. This fact produces two forces: (a) centrifugal force with a throwing out tendency which is similar at all points on the earth's surface, (b) an attractive force directed towards the moon. It is not of equal intensity on the surface but varies inversely proportionate to the square of the distance. Hence just facing the moon, the surface of the earth which is nearer by 4000 miles will have centrifugal force less than the gravitational force; so there will be a bulge of water. Similarly, the opposite side of the surface of the earth will experience a rising bulge of water because here the attractive force of the moon is lesser than the centrifugal force as it is 8000 miles further away from the moon's meridian. Just perpendicular to the above places, that is at poles, the centrifugal and gravitational forces balance each other and act towards the centre of the earth resulting in depressions and lowering of the sea level. So the highest points of the rise lie nearest to and farthest away from the moon.

Thus it can be said that tide is a wave moving westward with its crest directly under the moon. As the moon waxes and wanes in its monthly cycle, the height of the tide is also affected. Side by side, the sun's gravitational pull and varying positions of the sun, the moon and the earth also bring change in the magnitude of the tide. Hence the force creating the tide is regarded as the sum of 'harmonic-constituents' which vary harmonically with time. The horizontal component is also taken as the cause of tides though in any harmonic constituent the gravitational force may have any inclination. Thus a very convenient way of specifying the tide-generating forces is based on the assumption that the ocean is covering the whole of the earth.

Based on the above concept the time intervals between various types of tides and longer periodic variations have also been calculated on the basis of declination of the moon and the earth's rotation.

Limitations of the Theory. The bulge of sea water as proposed by this theory cannot take place unless water masses actually change their positions, that is, a horizontal movement is essential for this. Secondly, according to the theory, high tide should occur when the moon is exactly on its meridian. Similarly, all the places on the same longitude should have high tides at the same time. But in reality this is not the case. For example, the high tides at Liverpool and Leith, both situated on 8° W, have a difference of three hours. Thirdly, the depth of the ocean varies highly in an irregular way. The maximum and the average depths are found to be 5 miles or 2 to 3 miles respectively. Side by side, the ocean is not a perfect fluid but it moves under internal as well as external frictions. So the theoretical time proposed by the theory for a wave to round the earth would be more. As tidal waves are not free but forced waves and are a periodically repeated impulse, hence the oscillations are fixed though they slightly lag behind the originating body. Further, the water and land surfaces, as indicated in the preceding chapters on the bottom relief of the various water bodies and oceanic bottom, exhibit complicated features which obstruct the passage of the wave round the earth. That is why Airy regarded this theory as an erroneous approach to explain a collection of important physical facts though it is based on the very foundations of the law of gravitation upon which successive approaches were made. Hence it has been of historical value in the domain of Dynamical Oceanography.

The Dynamical Theory of Laplace. After Isaac Newton, the next big advance in the field of Dynamical Oceanography was made by the famous mathematical astronomer, Laplace, in 1755. He approached the phenomenon of tides as the water in motion. It is an approach from the viewpoint of dynamics which he dealt in his work *Mecanique Celeste*. He proved that the horizontal tide producing forces are more important than the vertical forces, because in the latter the periodical variation of the acceleration of gravity is absent. Under the impact of this oscillation there is a horizontal movement of water towards the moon's meridian where the bulge is created. As the earth rotates, different places automatically come beneath the moon and changes in the horizontal movements of water are observed. Hence, the water runs sometimes in one direction and sometimes in another in order to raise the water at points occupying different positions at different times. Having this approach to the problem of tides in combination with the canal theory it follows that canal would be divided into four parts in two of which the water is running in one direction and in the other two it is running in the opposite direction.

Progressive Wave Theory. The progressive wave theory developed a different approach in order to explain the varying intensities of tidal forces at different points on the earth's surface because the earth is a heterogeneous body and not a perfect fluid. Secondly, tide is seen on same longitude at different times, while simultaneously a lagging in the time of tide was felt on the same meridian away from the source. Thirdly, on a globe surrounded by water a tide appears to take the form of a tidal wave travelling from east to west. William Whewell in his paper entitled "Essay towards a First Approximation to a Map of Co-Tidal lines" in 1833 and G. B. Airy in his *Waves and Tides* in 1842,

presented the concept of progressive waves while explaining the varying intensity and varying amplitude of tides at different places. Whewell also prepared a map of the world on which were drawn the so-called co-tidal lines, that is, the lines joining points at which high water occurs at the same hour. He called his theory the 'Progressive Wave Theory', whereas G. B. Airy's approach is known as 'Canal Theory'.

The progressive wave theory at the outset observes the tides as the movement of a wave in the sea from the place of its origin under the moon's tidal influence. In a globe completely surrounded by water, the tides will have the form of a wave having crests (tide) and troughs (ebb). The length is measured from crest to crest, which will be half of the circumference of that latitude on which it is proceeding. The rate of the progressing wave is dependent on the depth of the water bodies in which it is moving. On a rotating earth the progress of the wave would be from east to west. Due to location of continental bodies, the movement of waves and the generation of progressive waves is hampered. The continents stretch from north to south, hence the generation of the tidal waves of great intensity in different oceans is not possible. Side by side, even if they do originate, a free east to west movement of tidal waves is not possible. The velocity of the tidal wave would be the square root of the depth of the body. The only unobstructed and open course for the tidal wave is found in the Antarctic Ocean having a width of great dimensions except at Cape Horn where it contracts to some 600 miles. Hence it is the progressive tidal wave of the southern ocean which determines the tides in other oceans stretching from south to north in the form of an elongated gulf joined with the Antarctic in the south.

This progressive wave originates under the continuous impetus of the tide generating force and is known as 'Primary wave'. The tidal wave has the same periodicity in its oscillation as the lunar tides, that is, a period of $24\frac{1}{2}$ hours for a complete lunar circle and 12 hours 24 minutes for half lunar circle.

So the water in the primary wave is at the greatest speed at the time of high water or at the spring tide. Contrary to it, the velocity is almost zero when the water is at its mean height. Further, when water is at its greatest depression, it is running backward with its greatest velocity. Thus it is supposed that under the influence of lunar force, the tide originates in the southern ocean and moves towards west in a form of a 'forced wave'. As it lags behind the impetus, low water appears at places which should have high water according to the equilibrium theory.

The birth of the secondary wave is due to the positions of land masses which check westward flow and divert the wave from the southern ocean towards the north. Further northward they strike the projections of the continents and give birth to a fresh set of tidal waves. These waves are known as the 'Derived Waves' which affect the tidal phenomena along the various coasts. For this process of wave diversion and movement of tidal phenomenon, the Atlantic, the Pacific and the Indian oceans may be regarded as the gulfs opening out in the southern

ocean. As the wave advances from south to north, it undergoes dissipation of energy but all the time causing tidal phenomena. The tidal energy is maintained by the periodic impetus given by the southern primary wave.

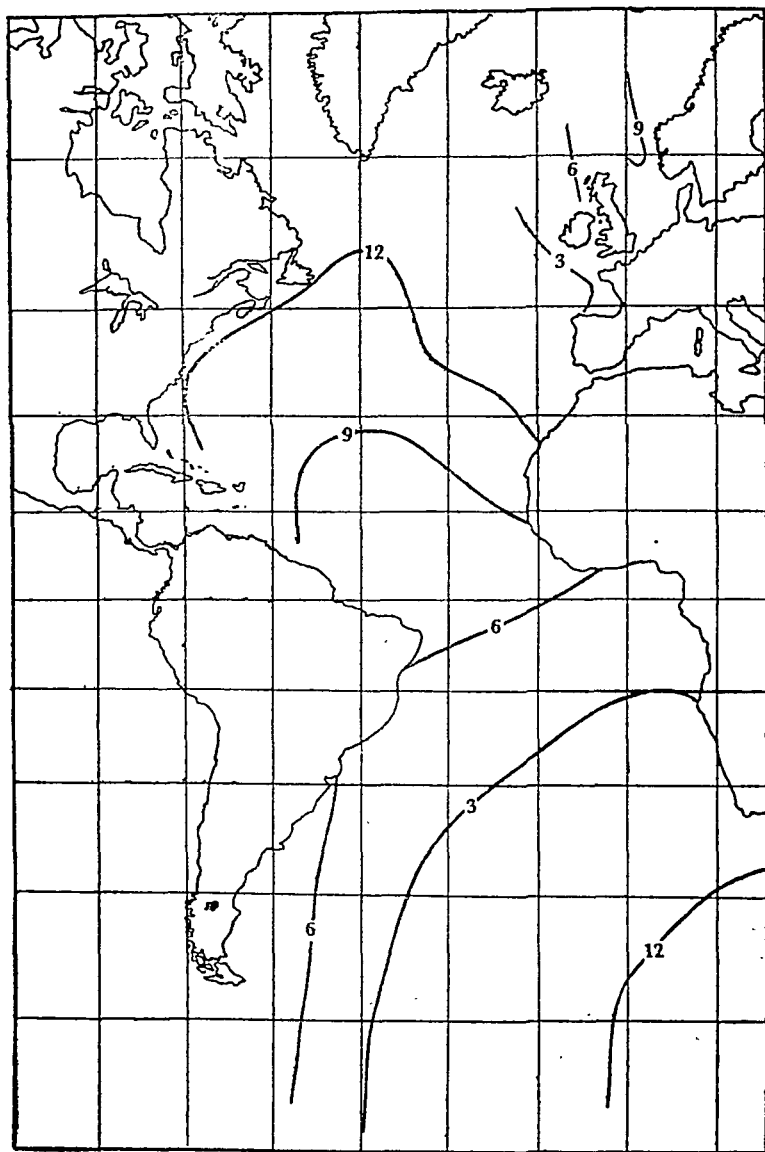


Fig. 77. Co-tidal lines of the Atlantic Ocean, based on the theory of a progressive wave (After Airy).

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All the waves have their origin in the Antarctica Ocean and then they further travel progressively up to the high northern latitudes in the Pacific, the Atlantic and the Indian oceans. With the advance of the wave there must be a series of fronts and these fronts may be represented by the co-tidal lines (lines joining the places having high tides at one time) which show how the wave progresses as it passes from south to north. The crest of the wave brings high water along the coast and the trough results in low water.

The tidal advance in the Atlantic according to the progressive wave theory is shown in Fig. 77 with the help of co-tidal lines. The numbers placed against the lines indicate the Greenwich time of high tide on the days of full moon. Based on observations, the following conclusions may be drawn. The tides travel more rapidly in mid-ocean than along the sea coast. The time of high water and low water occurs slightly later or l. gs behind as we go northward along the Atlantic coasts of Africa and South America., i.e., the age of tide (the time that had elapsed since its origin in southern ocean) increases northwards. The range of tides becomes greater as we move from Cape Horn to the Amazon due to the fact that the ocean becomes narrow and a consequent increase in tidal energy is found. The convexity of co-tidal curves increases northward due to the dissipation of energy, the varying depth and the form of the coast line. Hence the direction of the wave on the two coasts of the Atlantic is different, that is, on the coast of Europe it is from the west and on U. S. coast it is from the east. The same explanation may be given for the tides of other oceans. In general it can be said that the time, the nature and types of tide are due to the differences in depths of the ocean and the configuration of coast lines.

Progressive wave theory and tides of the British Isles. The progressive wave theory explains various anomalies and complications in tides which are characteristic of the waters of the British Isles. The tidal waves are mainly from the Atlantic Ocean where their direction is from south to north. But as they proceed, the direction is from south-west to north-east just south of England's southern coast. Here two offshoots are noticed. The northern one is divided in the North Irish Sea branch and the main westerly branch is going up to Scotland. The southerly offshoot sends branches in the South Irish Sea and the English Channel. Apart from the direction, the progress of the tidal wave is retarded and obstructed due to the continental shelf of the British Isles. Similarly, the friction of the coastal and submarine topography also retards the speed which is 600—700 miles per hour in south, whereas on the east coast of England it is only 40 miles per hour. The height of the wave is higher in the south-west part than elsewhere. At south-west coast of Ireland the height is about 10 feet, at Ushant it is 19 feet.

These peculiarities of the tidal waves are maintained throughout the English Channel, the Bristol Channel and the Irish Sea but a reversed and complicated condition is found where tidal waves enter a sea with two or more entrances. The tidal waves passing the north coast of Scotland have higher tides on the western part than on the eastern. The absence of tides in the stretch of water lying between

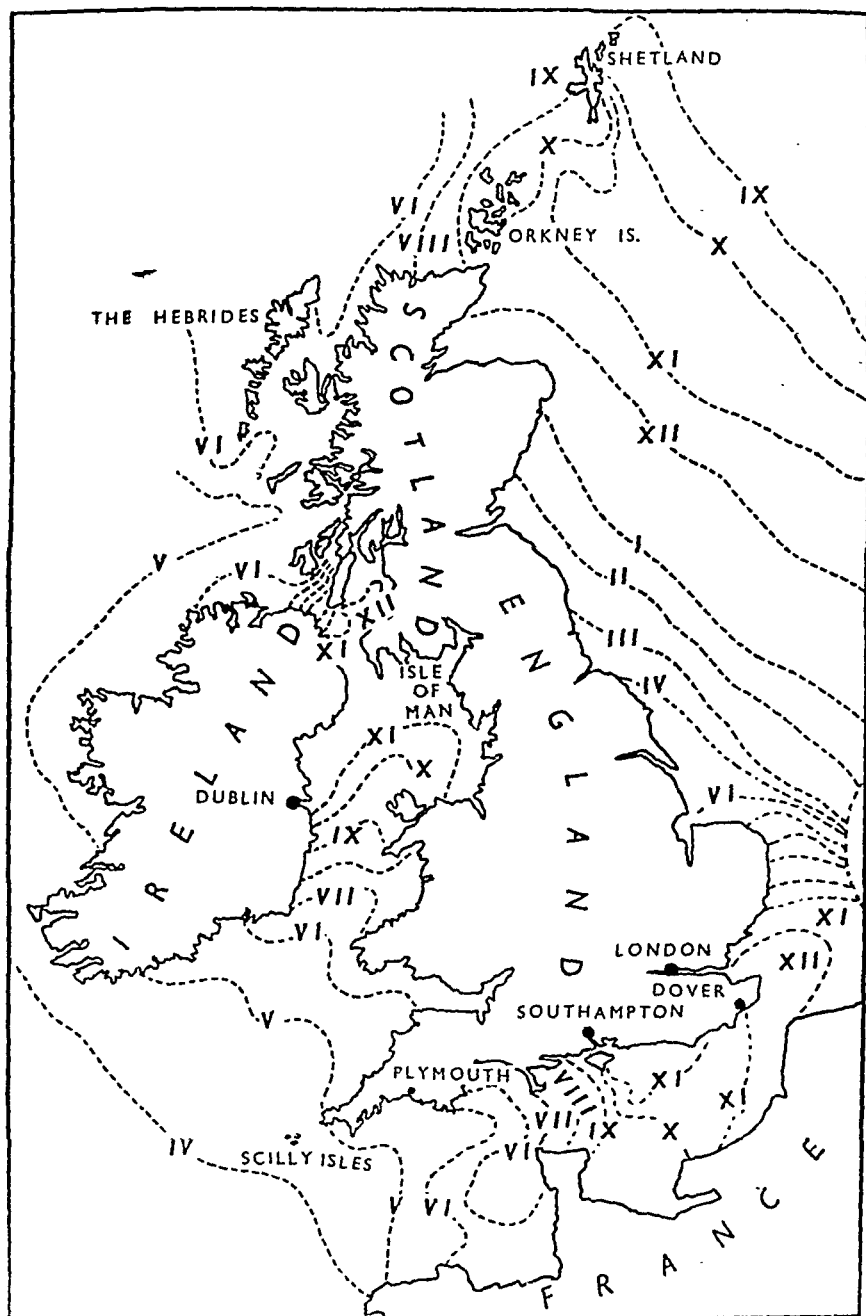


Fig. 78. Tides of the British Isles.

(By permission from, *A Textbook of Oceanography*, J. T. Jenkins. Copyright, Constable and Company Ltd., London).

Scotland and Isle of Wight is due to the travelling up of the waves from both the Spithead and Solent sides. So they are neutralised, thus resulting in no tides.

Limitations of the theory. The progressive wave theory has enjoyed a great popularity. The incapacities to explain certain aspects of tides with the help of this theory are due to the configuration of the bottom of the oceans and the friction on the sides of the water bodies. Under this theory 'the age of the tide' which increases from south to north is explained because the progressive wave theory assumes the tides originating in the southern ocean, while other coasts are affected by the secondary waves which take long time to reach the northern area. But as regards the distribution of the age of tides, the data so far collected prove that the time of the spring tides is almost the same in the Atlantic from Cape Horn to Greenland. This fact is contrary to the progressive theory according to which the age of the tide should be greater northwards. A difference in the type of tide is also noticed. In the Atlantic semi-diurnal tides have small daily irregularity whereas the tides of California have greater irregularity. Further, a study of the tidal phenomenon also proves that the tide appears to be a local or a regional phenomenon rather than a feature originating in southern ocean which is quite contrary to the theory.

Stationary Wave Theory. The stationary wave theory probably seems to offer the best explanation for local differences in tides, their varieties and their age. Dr. R. A. Harris of the U. S. Coast and Geodetic Survey first propounded this theory which is almost opposed to the ideas advanced by the progressive wave theory. The idea of the world phenomenon of tides being governed by the primary waves of southern ocean has been replaced by the separate regional occurrence of tidal phenomena in the water bodies such as the Atlantic, the Indian and the Pacific oceans.

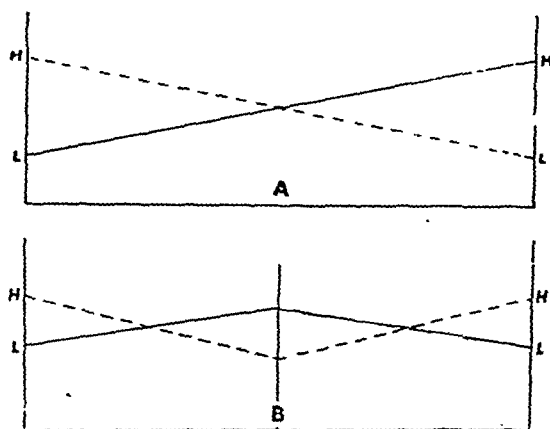


Fig. 79 (A) Uninodal and (B) Binodal oscillating systems.
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According to this theory, the solid earth with its water on it is made to oscillate under lunar force. The resulting waves are known as the stationary waves. For better explanation we can take an example of a rectangular tank or 'developing tray' containing water. If it is rocked from one side to another or just tilted, the level of water vibrates as a whole resulting in rising or lowering but the level at the centre will remain stationary as shown in Fig. 79 (A).

The water moves actually rhythmically from one end to another along a line which is called the nodal line and the rise and fall is greatest at the two points near the boundary of the basin. This is the case of a uninodal system because we take only one body of oscillation.

The second case as in Fig. 79 (B) will be binodal oscillating system when the lines of movements are two, that is, the high water is in the middle and low water occurs at the boundary. This may be visualised by taking two rectangular tanks of water alike in all respects and placing them together. The period of oscillation and its time should be such that high water or low water at the same instant should come at the continuous end of the basin. Thus considering it a single basin, the stationary wave movement will be on binodal lines. The high water will occur in the middle of the enlarged basin and low water at the two ends. Thus we may conclude that the stationary wave movement may be produced in basins of various shapes with single or more nodal lines. The oscillation of the wave is determined by the formula:¹

$$T = 2 l / gh$$

where l is the length of the tank, h is the depth of the tank and g the acceleration of gravity. This shows that each wave has definite period of oscillation. Hence the oscillation and the character of waves are different which are present in separate basins.

The direction of these waves depends on the character of the rocking. It changes with the rockings of the basin, though the central part remains stationary at level. An impulse is needed to set up the series of stationary waves of the kind which rapidly disappear after the dissipation of the energy. If a regular periodic impulse is maintained, such waves can be a regular phenomenon in the ocean bodies. The body responds most when the period of the force approximates the natural period of oscillation.

Following the above analogy, we have the earth with water on it and the forces helping the oscillation are the tidal forces of the sun and the moon which vary according to their changing positions. These periodic forces act upon the earth and make oscillation in the water body. Sometimes solar forces alone create such waves as in Tahiti, whereas at other place complications arise due to the combination of these forces. Among the main forces are the semi-diurnal forces of the moon and the sun with a period of 12h 25m and 12h respectively and the diurnal forces with a period of 24h 50m and 24h respectively. It is believed that these periodic forces help in giving rise to oscillation in all the different oceans, though it is modified by configuration of sea bottom,

¹ P. Lake, *Physical Geography*, p. 193.

depth of the sea and the rotation of the earth. The shape of the ocean or the projection of lands and bays presents different conditions of configuration and depth etc. for the action of tidal forces. They are also a barrier in the free movement of waves. Similarly, islands also present difficulty in their origin. Thus in the centre of the ocean there originates an amphidromic point around which oscillation takes place. There can be many such points according to the configuration of the basin. The next factor of importance is the depth which directly controls the amplitude of the wave because the friction diminishes the range of the tide. Hence in open ocean the height of the stationary wave is greater than in the shallow bays. In some cases, shallow bays do not give birth to the stationary waves due to friction. Further, the rotation of the earth gives a sort of gyratory motion to the oscillatory waves of the body. So in each ocean or in the sea basin, there is a similar system of rising and lowering of the level as developed by the rocking of the tank. Combined with the circular movement of the waves round the central stationary nodal point or the amphidromic point the amplitude of the wave and its movement is nil at the nodal point. The crest and trough of the waves bring about high and low tides. The time of tide increases from one side to the other depending on the rate and direction of oscillating swing. Such waves are best developed in those parts of the oceans which correspond most closely to the period of the tide producing forces.

Seeing the map of the world showing the configuration of bottom we may divide it into many natural basins of requisite length and width where stationary waves can originate in response to the tide generating forces. As shown in Fig. 80, Dr. R. A. Harris has developed natural basins of oscillation of the stationary wave in conformity with mathematical and physical principles. The Roman figures indicate in lunar hours the time of high water after the moon's transit of the Greenwich meridian. The dotted lines show the nodal lines, whereas the unshaded areas are those portions where depth and size do not allow the development of tides of appreciable magnitude. Hence these areas are influenced by the tides of the neighbouring regions. These oscillating systems as developed by Dr. Harris show the dominant semi-daily tides of the world in response to the semi-diurnal forces.

Further, we note that the time of the tides along different coasts closely resembles the actual observations, e.g., on east coast of U. S. A. high water occurs 12 lunar hours after the moon's passage over the meridian of Greenwich, the tides at the two ends of the Panama canal show striking differences, the behaviour of the tide on the shores of Tahiti island shows complete absence of lunar tidal forces and the presence of solar tidal forces.

The views of Dr. Harris about the stationary wave movement were modified by the factor of rotation of the earth. This factor gives a gyratory motion to the rocking of the wave and instead of swinging over the nodal line, it swings round a point called an amphidromic point—usually there will be several such nodal points according to the configuration of the basin. So the rotation of earth and the consequent amphidromic point will modify the whole scheme of oscillating system as previously given in the preceding maps of oscillating systems for the

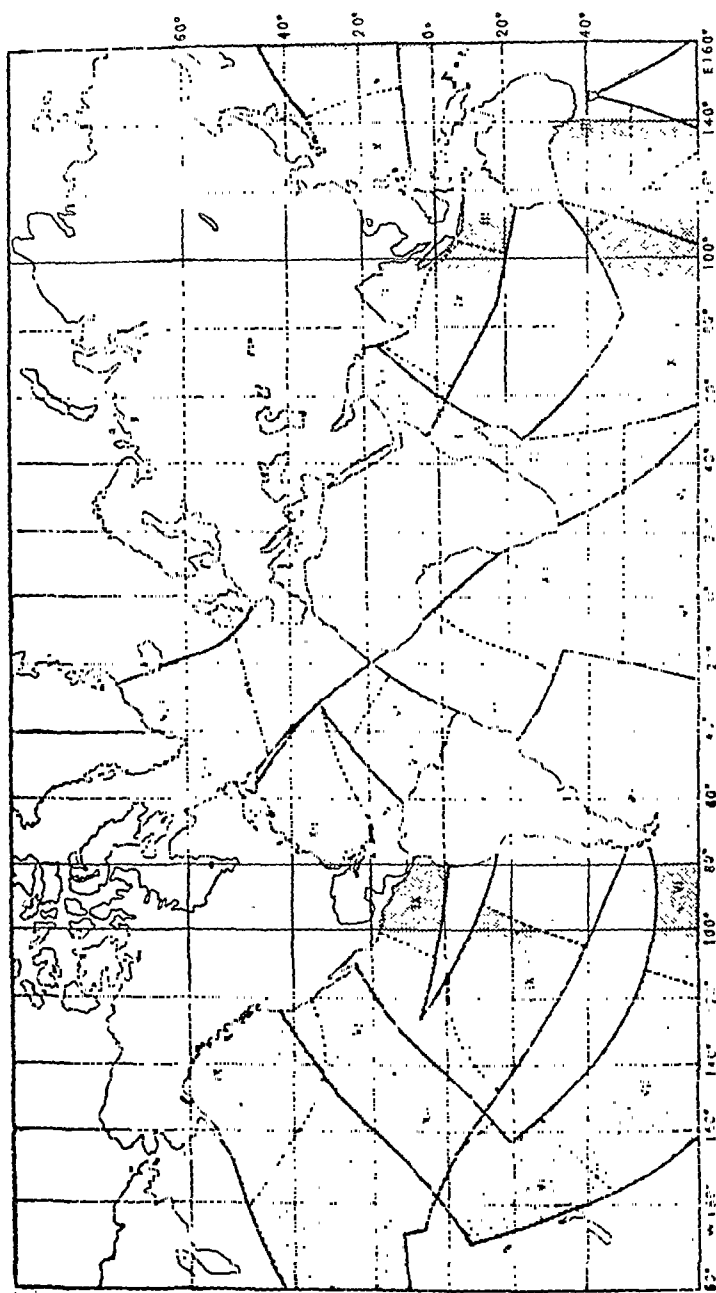


Fig. 80. Oscillating systems for the semi-diurnal tide producing forces. (After Harris).

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semi-diurnal producing forces according to Harris. Because of the paucity of observations and data an idea of the world map is premature, but a good idea may be formed by the map of the North Atlantic (Fig. 81).

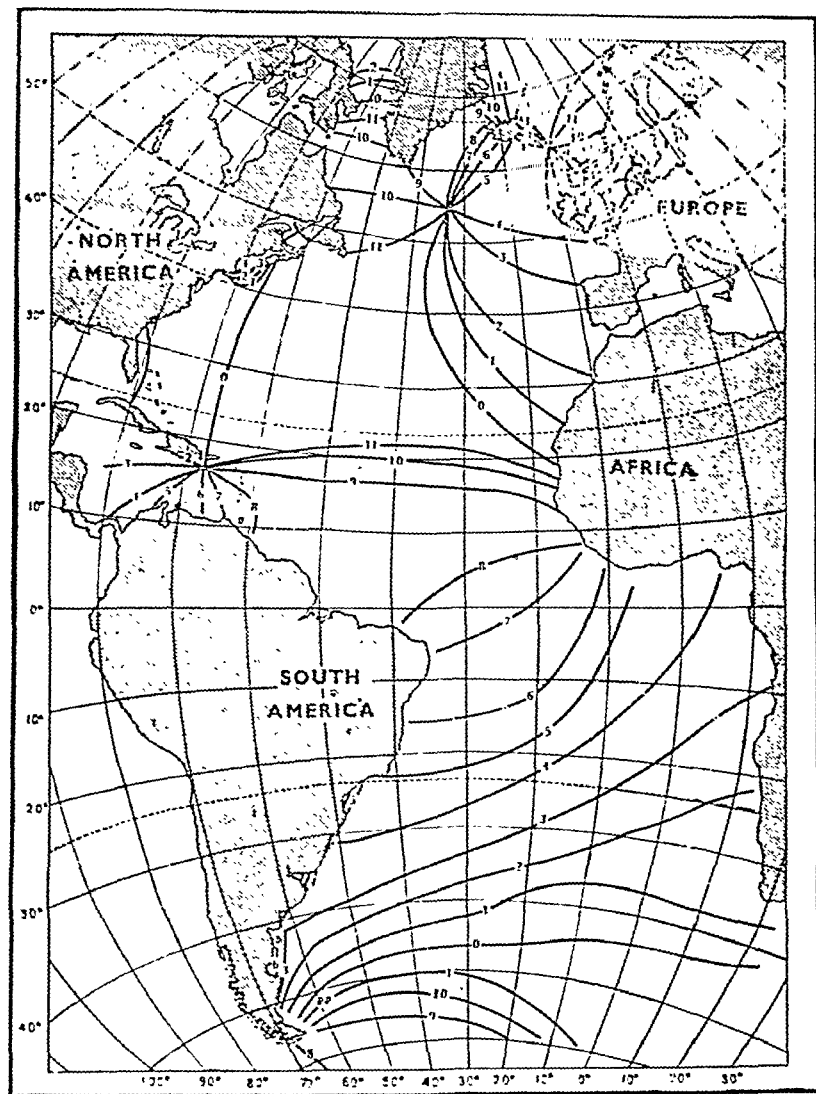


Fig. 81. Co-tidal lines of the semi-diurnal tide in the Atlantic Ocean (Sterneck).
(By permission of the publisher from H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans: Their Physics, Chemistry and Biology*. (C) 1942, Prentice-Hall, Inc., U. S. A.)

The present approach of this theory of stationary wave brings out clearly the phenomenon of tides. It provides to some extent the explanation of types of tides in different localities. Marmer rightly remarks, "Nevertheless, in the tide on the open coasts of the various oceans there is considerable evidence in favour of this newer theory of the making of the ocean tide and it does away with the conception of a single world phenomenon and substitutes regional oscillating areas as the origin of the dominant tides of the various oceans."

TIDE TABLES AND TIDAL PREDICTIONS

A tide table usually aims to furnish an accurate advance knowledge about tides and gives it in the form of tables predicting the time and the possible heights of the high and low water for every day of a calendar year. The tide table is generally published for six months or more in advance.

The tide tables in the modern form were first published by the British Admiralty in 1833, followed by the French Hydrographic Service in 1839 and U. S. Coast and Geodetic Survey in 1853. Generally, for the major ports the predictions about high and low water are given in tide tables but for the minor ports the tide tables give differences in times and heights of the tide as compared with the tides of the main and major ports for which daily predictions are given.

There are two main methods of tidal prediction which are based on the data and observations of the past years. These are known as harmonic and non-harmonic methods.

(1) Empirical (non-harmonic) method. It is based on the principle that the tide follows the moon. We have to predict the continuous variation in the height of the tide which depends upon the lunar and solar tidal forces and the relative positions of the sun, the moon and the earth. The interval known as lunitidal interval—the time elapsing between the moon's meridian passage and the times of high and low water at that port—is of prime value in the prediction of future tides because these lunitidal intervals are almost constant at a place. Hence the periodic changes of tides due to the phases and declination of the moon are adjusted accordingly.

It is also marked that the rise and fall of the water level, though following the moon's transit, is slightly lagged behind. This lagging of time is not similar at all places but almost the same at a particular place though the latter occasionally varies with the climatic changes. Thus rough alternations of high and low tides are made for the coming six months. Such predictions can also be made on the basis of old tide tables, where the heights and time of the tides are recorded.

The British Tide Table (Table 4) gives an example of the tide gauges and the associated astronomical data that are recorded for each day, on the basis of which the tidal predictions are made.

TABLE 4¹

*Tides and associated celestial phenomena.
Liverpool January, 1922*

Day of month	High Water		Low Water		Moon's transits	Lunitidal Intervals	Moon's declination	Sun's declination	The moon		
	h.	m.	ft.	h.	m.	ft.	upper lower	H.W. only	noon 0 1 0 1		
2	01	37	26.4	08	11	4.4	15 19	11 02	6.55	22 56	Apogee
	13	41	27.5	20	43	3.8	02 57	10 44			
3	02	21	25.7	08	44	5.2	16 01	10 53	3 17	22 52	
	14	16	26.7	21	15	4.8	03 40	10 36			

On 2nd January when the moon crossed the meridian below the horizon at 1 hours and 37 min., the resulting high tide is at 13 hours 41 minutes, i.e. the lunitidal interval is about 10 hrs. 44 minutes. Similarly, the moon crossing the meridian above the horizon at 15 hours 19 minutes would produce a high tide on the 3rd January at 02 hrs. 12 min, i.e. the interval is about 10 hrs. 53 min. ($2\frac{1}{2}$ hrs.—15 hrs. 19 min. = 8 hrs. 41 min. + 2 hrs. 12 min. = 10 hrs. 53 min). Hence it can be concluded that the high water at Liverpool is at an interval of $10\frac{1}{2}$ to $12\frac{1}{2}$ hrs. after the moon's transit.

Besides the moon, the solar influence also results in the decrease or increase of tidal height. If moon and sun are at the same meridian as at the time of full or new moon the height of the tide would increase, but if sun's passage is 6 hours later than moon's passage in quadrature then the tide thus produced by moon would be obtained by subtracting sun's tide.

Thus there is a continuous variation in the height of the tide which is also to be predicted along with the time of the tide. On the basis of the above table the upper and lower transits of the moon are taken which occur within twelve groups of intervals, viz., 0 to 1 hrs., 1 hrs. to 2 hrs. etc. Opposite each transit the height of high and low water is marked. Thus we get the average conditions of all the factors, e.g. the mean height of waters, and the mean lunitidal interval (between the transit and the following high water).

By this method we have mean time of the transits of the moon, mean height of high waters following the transit and the mean lunitidal interval for each group of interval as shown in Table 4. We plot in Fig. 82 the data, the mean time of transit on the X-axis and the lunitidal interval on Y-axis in one graph and mean time of transit on X-axis and height of the tide on Y-axis in the other. By joining the points we get smooth curves which will give the time of transit of moon, the lunitidal interval of the place and the height of the high water. This process will help in predicting the average luni-solar tide.

¹ Johnstone, *An Introduction to Oceanography*, p. 228.

For example, if we want to know the time and height of the tide on a particular day, we have just to look for the transit of moon on that place for that particular day. The time of the transit of the moon would give us the lunitidal interval as shown in Fig. 82. Hence the time of moon's transit + lunitidal interval = actual time of tide. The height of the tide would be obtained from the time of the moon's transit. So far we have the basis to predict the semi-diurnal luni-solar tide resulting when moon and sun are in the plane of the equinoctials but actually the case is different due to the effects of the two factors: (i) the orbits are ellipses so that moon and sun are at varying distance as tide generating forces are proportionate to the inverse cubes of their distances, and (ii) the planes of the orbits are not in the equinoctial.

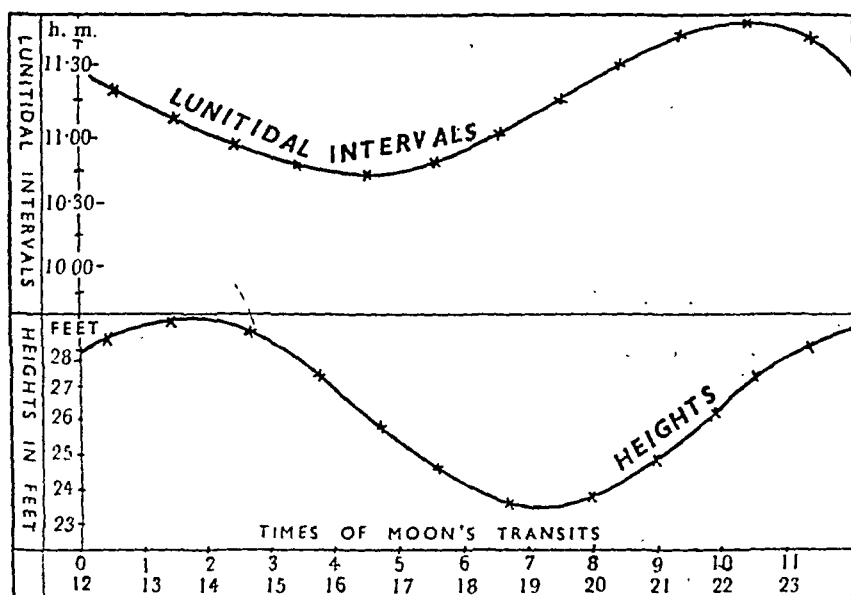


Fig. 82. Lunitidal intervals and heights in relation with the times of moon's transits.

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Moon's orbit is inclined at $28\frac{1}{2}^{\circ}$ and sun's at $23\frac{1}{2}^{\circ}$ to the equinoctial, that is, the phase (angular distance between the bodies) is always changing and we actually predict combined luni-solar tide. Thus the phase of inequality in the tide is due to the effect of solar semi-diurnal tide on the lunar semi-diurnal tide. The lunar semi-diurnal and solar semi-diurnal tide is accompanied by a diurnal tide, and one of the two tides of each day is slightly higher than the other. Therefore, the following considerations are necessary in order to obtain accuracy.

(a) One for the lunar, tropical, diurnal inequality, that is, the diurnal effect on the phase inequality of change in the moon's declination. Its period is about one month.

TABLE 5¹

Times of moon's transits	Mean times of moon's transits H. M.	Mean heights of the H. W. of tides following the preceding transits	Mean lunital intervals H. M.
0 - 1 hr. 12 - 13	0 30	23.7	11 21
1 - 2 „ 13 - 14 „	1 30	28.8	11 07
2 - 3 „ 14 - 15 „	2 30	28.6	0 57
3 - 4 „ 15 - 16 „	3 30	27.6	10 43
4 - 5 „ 16 - 17 „	4 30	26.2	10 35
5 - 6 „ 17 - 18 „	5 30	24.7	10 39
6 - 7 „ 18 - 19 „	6 30	23.3	10 50
7 - 8 „ 19 - 20 „	7 30	23.1	11 19
8 - 9 „ 20 - 21 „	8 30	23.9	11 43
9 - 10 „ 21 - 22 „	9 30	25.3	11 54
10 - 11 „ 22 - 23 „	10 30	26.9	11 49
11 - 12 „ 23 - 24 „	11 30	28.1	11 36

(b) One for the solar tropical, diurnal inequality, i.e. diurnal effects on the phase inequality of changes in the sun's declination. Its period is one solar year.

(c) and (d) One is for lunar and the other for solar tropical semi-diurnal inequality. Its period is half month and $\frac{1}{2}$ solar year respectively as changing declination affects the principal lunar and solar tides. These corrections are based on the changing distances of the moon and the sun from the earth as they affect the principal lunar and solar tides, i.e. the effect on the phase inequality of the changes in the moon's distance (semi-diurnal inequality) and the sun's distance.

In the end it can be said that this non-harmonic system is fairly good for the predictions of the semi-diurnal types of tides but unsatisfactory results appear in the case of mixed and diurnal types of tides.

(2) **Harmonic method.** The harmonic analysis conceives the sum of the rise and fall of a number of simple tides. The average wave

¹ Johnstone, *An Introduction to Oceanography*, p. 232.

is thus affected by many inequalities where values are found empirically and predictions regarding height and time are corrected. These are known as harmonic components of the tide. Actually various curves are drawn showing the tides due to various components and by that the general characteristics and nature of the tide is predicted. The character of the graph prepared like this would be to break into many partial waves, each of which itself is absolutely periodic and harmonic and shows the tides due to various components. When all these partial waves are combined they produce actual time and height of the tide. This new method of tide tables and tide prediction was propounded by Lord Kelvin (1867), and Sir George Darwin. Prior to this the tide tables were prepared in 17th or 18th centuries by this method, though it was not so developed as it is now.

The harmonic analysis of the nature of tide considers the simple tide as a summation of a number of components or tidal constituents, such as moon and sun as the major forces and various other factors arising due to their declination, elliptical orbits and varying distance. Suppose we take the two constituents sun and moon only as the tide producing forces. The time and the height of the solar tide would be same at one time at a place but lunar tide at a place is 50 minutes later. Hence the curve of the height of tide for 15 days would show a decreasing tendency, i.e. for 7 days the height is at the sea level and for the remaining 7 days it is below the sea level. It is observed that all these minor tides have a harmonic form, though in shallow water they become non-harmonic, i.e. the front of the wave becomes steeper than its rear.

TABLE 6¹
Tidal Constituents

Semi-diurnal constituents	Diurnal constituents	Long period constituents
M_2 Principal lunar	K_1 Luni solar declinational	Mf Lunar fortnightly
S_2 Principal Solar	O_1 Larger lunar declinational	MSf Lunar fortnightly Variational
N_2 Larger Lunar Elliptical	P_1 Larger solar declinational	Mm Lunar monthly, Lunar monthly
K_2 Luni-solar declinational	Q_1 Lunar Elliptical	evectonal, Three monthly
V_2 Larger lunar Evectonal	J_1 Supplementary lunar elliptical	
L_2 Smaller lunar Elliptical	OO_1 Second order lunar declinational	Ssa Solar semi-annual
T_2 Solar Elliptical	ρ_1 Lunar evectonal	Sa Solar annual,
$2N_2$ Second order lunar elliptical	$2Q_1$ Second order Lunar elliptical	Nineteen yearly.
μ_2 Lunar variational		
λ_2 Smaller Lunar evectonal	σ_1 Lunar variational	

¹ *Ibid*, pp. 242-43.

The tidal listed components in Table 6 have periods that are deducible correctly. Out of these two components M and S denote the principal solar and lunar components, whereas suffixes show their periodicities. These mainly specify the characteristics of the tides. Theoretically, to represent a simple tide, about 20 components are required. The characteristic of a simple tide and its rise and fall is represented by a cosine curve as shown in Fig. 83.¹ The simple tide is composed of two

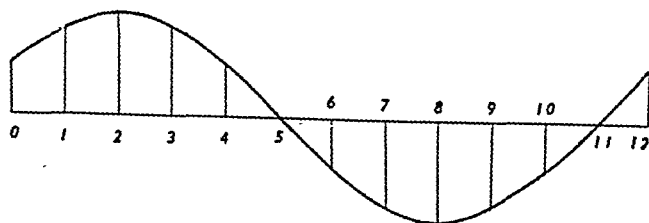


Fig. 83. A simple Tide Curve.

characteristics : amplitude (vertical distance between the highest and the lowest point in relation to sea level) and epoch (the interval between the high water and the time of the meridian passage of the tide producing body). They are regarded as the tidal constants. The evaluation is based on the equation.

Height of tide = $a \sin (Bt + c)$ where a is amplitude, Bt is the epoch and c gives the initial phase of the wave at zero time.

On the basis of these harmonic components, we can also distinguish various types of tides. The types of tides depend upon the diurnal inequality which in turn depends upon the daily and semi-daily constituents of the tide K , O , M_2 . So the ratio of $K_1 + O_1 = M_2$ (which is the measure of the amount of the inequality in the tide of any place). When the ratio is less than one-half, then the tide is semi-diurnal; if it is between $\frac{1}{2}$ and 2, then it is a mixed type; and when it is greater than 2, then it is daily type of tide.

While making the prediction of tides on the basis of harmonic analysis the only necessary thing is to know about the time of the meridian passage of the particular tide-producing body for a particular day and after that by adding the heights of the simple tides at a particular time we can determine the height of the tide for that date. The cosine curve of the simple tide is of immense help in the prediction. Prediction by this method becomes very difficult because in a single year there are about 1400 high and low water tides and we have to take at least 20 components into our consideration to predict one simple tide.

As early as 1872, a mechanical device was put forward by Lord Kelvin to predict the tide. This machine was named Kelvin Tide Predictor. Later on, William Ferrel, a tidal mathematician of the U. S. Coast and Geodetic Survey, invented 'Ferrel Machine' in 1882

¹ Marmer, *Tides*, p. 186.

to record the time and the height of the tide directly on dials. But Dr. R. A. Harris of the U. S. Coast and Geodetic Survey, with the help of E. G. Fischer, completed a new machine in 1910. The functions of the machine were: (i) the drawing of the curve of the predicted tide, (ii) marking the times of each high and low water on the curve, (iii) showing the time and height of low and high water on the dials, and (iv) marking of the height of tide for any desired time.

Effects of Tides. The phenomenon of tides which is so universal in its geographical distribution is of immense value to human beings. Tides are the source of great energy. This energy is due to the rise and fall of the sea water under the impact of tide generating forces, but it is not utilized in an appreciable quantity though large scale projects have been proposed for the future.

There are many difficulties in the use of tidal power because of the variation in the range of tide according to the phases of the moon. If the average range of the tide is less than 10 feet, the economical use of power is not possible at that point. It has been observed that areas of large range of tides are mostly situated away from the population centres, i.e. in the Arctic regions etc. Hence the use of tidal power is also not economical.

On the other hand certain advantages are also gained by the tides. Major ports of the world are found to be located on the rivers, away from the sea coasts, e.g. London is 50 miles away from the mouth of Thames and Hamburg is 75 miles up the Elbe river. But the tidal water of the sea moves into these rivers and brings ships just near the ports. This fact points out the utility of the tides in the commerce and trade of the world and proves that the tide is a bond that keeps the river channel up to the port in closest contact with the open sea. Many other advantages are gained side by side, i.e. the increase in the depth of the channel, the lowering of the freezing point of the water, the clearance of the river mouth of sand bars and other marine deposits, and lastly, the disposal of the sewage of a large number of commercial urban centres.

The tides are the agents of distribution. Biologically, they distribute and re-distribute the planktons and nektons along the coastal waters which help in the fishing industry. They also control the distribution and deposition. Thus, the influence of the tides on the living world of the sea creatures as well as men is of overwhelming importance.

Chapter 13 | DYNAMICS OF OCEAN CURRENTS

The ocean current is the general movement of a mass of water in a fairly defined direction under the various forces, internal as well as external. It is one of the most important features of sea water which is overwhelmed by various types of motions.

With the development of the knowledge of ocean currents many theories and ideas have been put forth regarding their distinct regional pattern and their cor-relation to various factors. Early writers held the view that all currents had westerly trend, attributed to the rotation of the earth and the gravitational attraction of the moon. Few others maintained the idea of the stress of prevailing winds and the difference in the sea water temperature to be the causes of currents. According to Leonardo da Vinci the specific gravity of the sea water had also an important part to play in the origin of the currents. This was also believed by the modern oceanographer Nansen. But actually it was Alexander von Humboldt (1816) who attributed various currents to the physical properties of sea water such as temperature, salinity, ice melting, evaporation etc. According to him currents are not the result of one factor but the combination of factors.

The following are the factors which control and explain the phenomenon of currents.

1. Factors in relation to earth's nature:
 - (a) Gravitational force.
 - (b) Deflective force by earth's rotation.
2. Factors outside the sea or ex-oceanic causes:
 - (a) Atmospheric pressure and its variations
 - (b) Winds and the frictional force.
 - (c) Precipitation.
 - (d) Nature of Evaporation and Insolation.
3. Factors within the sea water or sub-oceanic causes:
 - (a) Pressure Gradient
 - (b) Temperature difference
 - (c) Salinity
 - (d) Density
 - (e) Melting of Ice.

4. Factors modifying the ocean currents:

- (a) Direction and the shape of the coast line
- (b) Seasonal variations
- (c) Bottom topography.

FACTORS IN RELATION TO EARTH'S NATURE

(a) *Gravitational force.* It is a well observed fact that anybody in or near the earth is subject to the force of earth's gravity which is responsible for the centripetal and centrifugal forces. Consequently, any moving body whose position is related to the earth will also be governed by this force. If no force other than the gravitational one is acting on a surface, it could be observed that a mass can be moved along a level surface without expenditure of work and that the amount of work expended or gained by moving a unit mass from one surface to another is independent of the path taken. The amount of work (W) required to move a unit mass a distance h , along the plumb line can be given by the formula: $W = g^h$ (g is acceleration due to gravity).

Thus any particle of the ocean mass is subject to a pure gravitational force directed towards the central region of the earth. The magnitude and the dimensions of the acceleration of gravity of a moving mass vary with latitude and depth. The normal value at pole is 9.83205 and at equator it is 9.78027. That is, the gravity increases poleward. Similarly, with depth the force also increases. The resultant effect on the currents would be directed towards the centre.

(b) *Deflection due to the earth's rotation.* [The rotation of the earth from west to east results into the deflective or coriolis force which, otherwise weaker, acts as an important controlling factor of the currents. The general tendency of the water at the surface in equatorial region is to reach the polar seas. But due to the rotational force, the currents are deflected, as observed in the Baltic and the Mediterranean Sea.] There it was found that the wind current existed up to 5 m. only, and on many occasions its speed was registered below 3 on Beaufort's scale, thus unable to develop strong currents. Similarly, observations are made at the time when strong wind blew, then the speed of the current was 3.7 miles per 24 hours. By computing the actual direction of the current and the wind, the deviation on the right was made up and was attributed to the rotation of the earth.

This deflection of the current, as computed and summarized by Ferrel in his law, is the result of the movement of any particle on the rotating earth which is acted upon by two forces, the force of gravity in the direction of AD towards the centre at right angles to the surface and the centrifugal force in the direction of DB at right angles to the axis of rotation as shown in Fig. 84(A). The former is directed down slope, as against the up slope direction of the latter. AD will be at right angles to the surface and hence can have no tendency to make the particle move in any direction. As the force DB is oblique to the surface, it will not only lift the particle but will cause it to slide towards equator or pole. "The motion," says Sverdrup, "will no longer be accelerated if the component of gravity acting along the isobaric surface is balanced

by the coriolis force." An example is afforded at equator where the centrifugal force is directed at right angles to the surface and is just opposed to the force of gravity. At the poles the deflecting force is completely at its maximum, hence at the poles there is no movement of the water particle.

Again, due to the ellipsoidal shape of the earth, the force of gravity is not directed exactly towards the centre and is not at right angles to the surface except at the poles and the equator. At other places, as P. Lake mentions, "it may be resolved into two components, one AD at right angles to the surface, the other DE tangential. The former presses the particles against the surface, the latter tends to move it towards the pole. The centrifugal force in DB direction is at right angles to the axis of rotation and which may be resolved into two components, one DA at right angles to the surface, the other DC tangential. The former makes the particle a little lighter and the latter tends to move it towards the equator. When the particle is at rest on the rotating earth the forces DE and DB must balance each other."

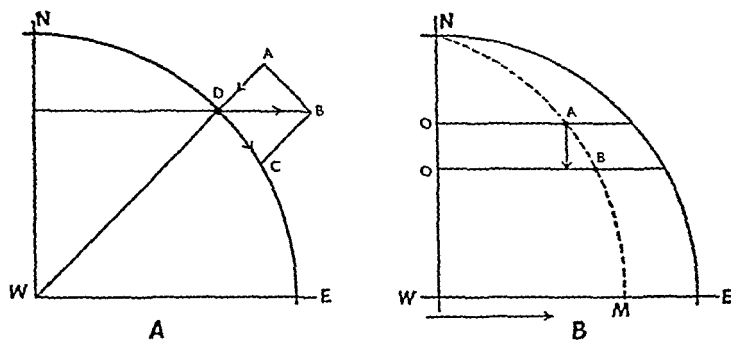


Fig. 84. Effects of deflection force upon the moving particle.

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This deflecting force as calculated is a function of the latitude, that is, it increases from the equator to the pole. Moreover, it is also proportional to the speed at which the mass is moving and is directed on the right at right angles to the velocity. Hence the resultant movement of the water mass, if it is moving towards south, will have westerly velocity conferred on it at 'A' by the earth as shown in Fig. 84(B). That is, it attains the velocity of a point on the earth's surface in that latitude OA. If it moves southward the same velocity is preserved. But at latitude OB the velocity of a point B on the earth's surface is greater than at latitude OA, therefore the particle would move slowly. Thus, it lags behind and moves towards right. Similarly, the particle moving to north will deflect towards east as it attains the latitude OA. Opposite to this in the southern hemisphere, the deflection is directed to the left. If the water particle is moving towards west, it is opposed to the direction of rotation, i.e. the resultant velocity of the particle is

the earth's velocity at point in question minus the proper motion of the particle. The velocity of the particle is now less than it was relative to the velocity of the earth beneath it. Hence, the centrifugal force must decrease. The poleward force gets unbalanced and the particle moves slightly towards north along meridian NE, instead of moving directly to west, that is to right.

Again, in Fig. 84(A) if the particle moves from west to east the centrifugal force at D on meridian NE is represented by DB. The gravitational force is represented by AD. When this DB force is balanced by the poleward force AD, due to the tendency of the particle to move to a position nearest to the earth centre, there is no motion of particle. Due to eastward movement in the direction of the rotation, the velocity increases and the component DB also increases, while the poleward component AD remains the same. Therefore, D moves slightly towards the equator along the meridian NE, *i.e.* to right.

[In the northern hemisphere, the isobaric surfaces slope upward to the right and in the southern hemisphere upward to the left. The resultant moving water turns towards right in the northern hemisphere and left in the southern hemisphere. Hence, there is no longer north to south or *vice versa* flow. But water moving from equator to pole will have south-west direction in northern hemisphere and north-west direction in southern hemisphere. On the other hand, the water moving from the poles will have north-east and south-east direction respectively in northern and southern hemispheres.]

Thus two types of eddies are found in the northern hemisphere. The water flowing from the equator would gradually turn to the east and then back to south as it sinks towards the sea bottom. The water flowing from the pole would gradually turn round to the west and then back again to north, and would again sink beneath the surface. A similar but reverse circulation is found in the southern hemisphere.]

EX-OCEANIC CAUSES

(a) *Atmospheric pressure and its variations.* Atmospheric pressure is of primary significance in the fundamental equation of motion. The ocean acts as a barometer which reflects the moods of the atmosphere in the form of variations of level and the movement of currents. Over regions of greater atmospheric pressure, the level of the sea is found to be lowered, and *vice versa*. Since mercury is thirteen times as heavy as sea water, it follows that a change in barometric pressure of one inch should be reflected by an inverse change of thirteen inches in the level of the sea. Hence, the isobaric surfaces are not parallel to the sea level (all points subject to the same pressure lie on an isobaric surface) and the resultant pressure is also not that single force perpendicular to the isobaric surfaces, directed upwards.

In a liquid mass under uniform gravity this surface is horizontal due to unequal pressure. According to Proudman,¹ due to differences in atmospheric pressure the sea surface cannot remain in level. But since isobaric surfaces within the sea will be in level, it follows that a deficiency of

¹ Proudman J., *Dynamical Oceanography*, p. 38.

atmospheric pressure must be balanced by the extra pressure due to a column of water of greater height. An upward gradient of sea surface will therefore correspond to a negative horizontal gradient of atmospheric pressure. The ratio of the surface gradient of the sea and the corresponding gradient of the mercury barometer will be the negative ratio of the densities of mercury and sea water.

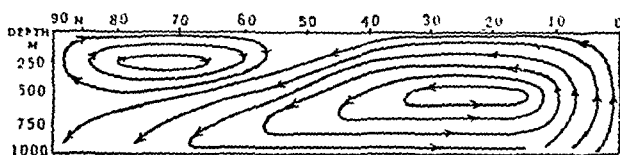


Fig. 85. A meridional section between 0° and 90° (shown on the flat) with the deduced directions of water circulation on the basis of isobaric surfaces.

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As the pressure increases on the surface of the sea, so the specific volume (that is, the volume of the unit mass of sea water) decreases due to compressibility. The result is that a surface current moves outward from the areas attaining higher sea level towards that of the lower level, as shown in Fig. 85. Similar results are obtained by Knudsen, a Swedish oceanographer, who found that the currents between the North Sea and the Baltic Sea move to balance the higher level (or low atmospheric pressure) of the Baltic and lower level (high atmospheric pressure) of the North Sea. The resulting current is from the Baltic towards the North Sea through the strait in between them. The velocity here is directly proportionate to variations in the pressure.

The inter-relationship between variations of pressure and the sea level had been computed by Sir Clark Ross at Port Leopold in the Canadian sector of the Arctic Sea, from November 1843 to July 1849. Similar statistical study was also made in 1924 by Doodson. According to Sverdrup there is a difficulty in determining directly the pressure on any level surface or the topography of any isobaric surface under the sea level, as it is varying continuously due to other atmospheric and sea factors.

The difference of level or the pressure gradient results in the formation of gradient currents, calculated by the gradient-equation which connects the inclination of the sea surface to the surface current. C. S. Durst (1949) has used gradient equation to compute mean-variation of the surface elevation of the North Atlantic along $42\frac{1}{2}^\circ\text{N}$ from 10°W to 70°W in the months of December and January. He found a fall of 137 cm. in December and 113 cm. in January. Across the strait of Dover, similar gradients are found by J. N. Carruthers. The currents have 3 miles a day as mean value with a direction from the English Channel to the North Sea, the cause being a rise of 0.743 mm. per km. from the English coast to the French coast. The width of the strait is

19 sea miles (35.2 km.), hence the total rise from the English to the French coast is $35.2 \times 0.743 \text{ mm.} = 2.62 \text{ cm.}$

(b) *Wind and Frictional Forces.* [Wind blowing along the surface of the sea exercises a very considerable force in the movement of sea water. It glides with friction over the sea surface and drags onward the pile of water with a considerable modification of the theoretical directions of the current to a remarkable depth.]

A close correspondence between the world map of currents and the wind circulation would, no doubt, reveal a close correspondence between the two. [The trade winds sweep away the waters of the oceans from east to west in the form of equatorial currents and the westerlies from west to east in the form of Gulf Stream, Kuroshio etc.] It was Karl Zoppritz in 1878 who could mathematically investigate that a steady blowing wind brings about through friction a surface flow in the direction of the wind. This moving surface layer in its turn exerts certain amount of friction and drags the lower layer with it. Hence after a considerable period, the whole mass of water from top to bottom would be moving in the direction of the wind. The total transport of water that circulates depends upon the square of the wind velocity and the latitude.

Thus it is believed that it is primarily the friction by the wind which sets in motion the sea water. The frictional force or the shearing stress is produced when layers are slipping relative to each other, and is proportional to the rate of shear normal to the surface on which it is exerted. Rossby was perhaps first to calculate the exertion of wind on the sea water. Wust, Rossby and Montgomery (1935) by making wind measurements concluded that at moderate wind velocities, the sea surface has a character of a rough surface, with roughness having a length of 0.6 cm. During observations Rossby found that as regards moderate and strong winds the roughness is independent of the wind velocity and is equal to 0.6 cm. Similar results were derived by Ekman in 1905, through the study of slope of the sea surface during a storm in the Baltic in 1872. Contrary to the above, at low wind velocities Rossby (1936) examined different conditions. The sea surface appeared calm and smooth due to the existence of a laminar sub-layer—an absolutely smooth surface—and so the wind stress would also be reduced to one-third of the former. Sea surface is considered smooth at wind velocities below 6 to 7 m/sec.

The result of the friction and the stress of the wind is visible in many ways. It primarily determines the direction of the current and hence the velocity of surface current. According to Sverdrup¹ this stress of the wind is proportional to the square of the wind velocity. Generally it is noted that the velocity of the current is $1\frac{1}{2}\%$ of the wind velocity, i.e. a 50 m.p.h. wind would produce a current whose velocity is $\frac{3}{4}$ m.p.h. The ratio between the velocity of the surface current and the wind force depends upon the stress of the wind and the value of eddy viscosity. Rossby (1932) and Montgomery (1935) have introduced the latter factor, along with the wind current. The eddy viscosity, which

¹ H. U. Sverdrup, *Oceanography for Meteorologists*, p. 125.

Ekman took to be constant, is supposed to depend upon the mixing length, that is, it is small near the surface, increases to maximum at a short distance below the surface, and further decreases to zero at the lower boundary of the wind stirred layer (when other currents are not present). This theory leads to a series of complicated expressions for the angle between surface currents and stress of the wind factor and the depth of the wind current.

Now comes the question regarding the direction of the current produced by the prevailing winds. Karl Zoppritz pointed out that under wind force the whole mass of water would move in the direction of the wind. Findlay objects to it, as he says that the force of the wind is active only up to 5 or 6 fathoms, and only a superficial water layer moves in that direction. The velocity no doubt lessens with the depth in proportion to the distance below the surface, as the dragging influence is decreased.

However, another criticism that was raised against Zoppritz was that he did not include the action of the deflecting force of the earth's rotation. It was first noticed by Nansen, while studying the drift of ice in the polar seas in 1893-96 on the 'Fram' expedition, that the ice was not moving in the direction of the wind but was deflected $20-40^\circ$ to the right. From the above he concluded that the direction of motion of each water layer must deviate to the right of the direction of movement of the overlying water layer, because this lower layer is actually swept by this overlying layer and not by the surface winds. Nansen's observations were proved mathematically by Ekman who believed that the angle of deflection between the resulting current and the prevailing wind would be 45° on the right in the northern hemisphere and 45° towards the left in the southern hemisphere. This deflection, according to Ekman, remains constant at the surface all over the oceans. Though near the coast the wind-driven current will be deflected to the right, yet the deviation will be affected mainly by the direction of the coast line and the angle would vary from $0-53^\circ$ depending on the angle between the coast line and the direction of the wind. But in the lower layers which are stirred by the upper water, similar deflection is not found. The angle of deflection increases with the depth and, as found in Ekman's spiral diagram (Fig. 86), a complete reversal in the direction of the current is found at the bottom.

The actual observations made by many oceanographers show different results from that of Ekman's theory. C. S. Hurst (1924) points out a 40° deflection of the current in the northern hemisphere. He gives the table of deviation in various latitudes (Table 1).

Further, C. Forch found the inter-relationship between the wind direction and the surface current in the Mediterranean and a deviation of 42° angle was found on the right. In the North Equatorial current, similar observations show that the trade wind blows from the north-east direction, whereas the resulting current is from east to west. P.M. Galle (1858-1904) observed a deviation of 49° to the left in the South Equatorial current, and an angle of 44° to the left in the west wind drift.

The angle of deviation varies according to the depth of the sea, the latitude and the wind velocity. In the shallow water the angle of

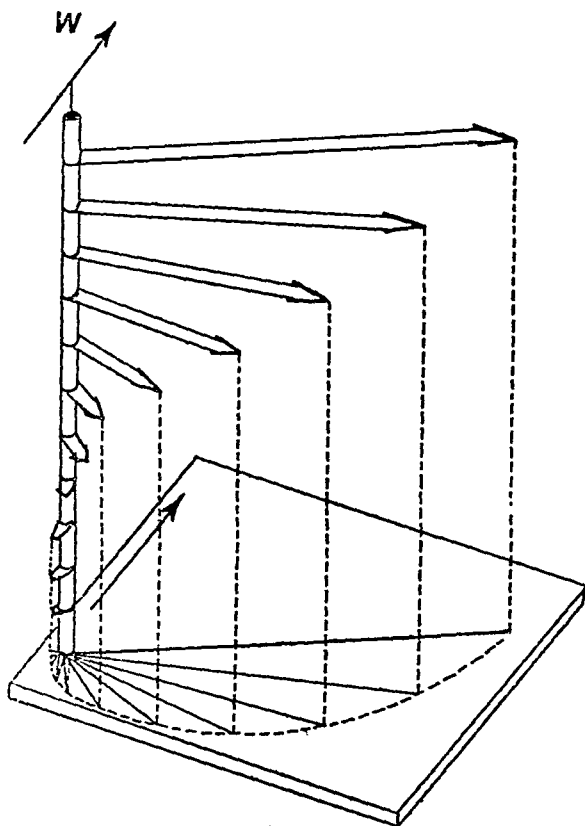


Fig. 86. Schematic representation of a wind current in deep water, showing the decrease in velocity and change of direction at regular intervals of depth (The Ekman Spiral). 'W' indicates direction of wind.

(By permission from *Oceanography for Meteorologists* by H. U. Sverdrup. Copyright 1945. George Allen and Unwin Ltd., London).

TABLE I
Showing Deviation¹

Ocean	Latitude	Longitude	Speed of the wind cm/sec.	Angle of deviation
N. Atlantic	47°-53° N	10°-30° W	8·5	34 R
Indian	10°-20° S	90°-110° E	11·5	29 L
	20°-30° S	100°-105° E	11·5	42 L
N. Pacific	30°-40° N	40°-110° E	12·2	30 R
	10°-20° N	150°-170° W	23·0	27 R
S. Pacific	20°-30° S	100°-170° W	7·8	34 L

¹ Proudman, *Dynamical Oceanography*, p. 176.

deflection is comparatively smaller than that of the deep seas. Generally, less deflection is found at the surface and a less rapid increase of the angle of deflection is found with the depth. Sometimes the direction of wind is similar to that of the current. L. E. Dinklage made a statistical analysis in 1888 at a station in the Baltic Sea where the depth was 12 m. Here the angle of deviation was 24° . R. Witting (1909) studied in the Baltic, in the Kattegatt and in the Lake Ladoga, where the depth ranged between 9m to 65 m. The Baltic and the Gulf of Finland were studied by E. Palmén (1928), who classified the surface gradients according to the direction and speed of the wind. When the wind speed was 4 m/sec. the deviation amounted to 23° in the Baltic and 9° in the Gulf of Finland.

Apart from the above, latitude is also considered to be an important fact to determine the deflection of the current. This fact was totally disregarded by Ekman whenever he stated that mean variation of angle is found all over the oceans. At the Equator the angle of deflection between the current and the wind direction must be 90° (this assumption is based when the ocean is of infinite depth) and it must increase with the latitude. But actual observations revealed that the angle of deflection would begin to decrease in the neighbourhood of the Equator and be zero at the Equator. Wind velocity is also an additional factor in this consideration. According to Rossby and Montgomery, the deflection of wind current at 5° latitude increases from 35° angle at a wind velocity of 5 m/sec. to 43° at a wind velocity of 20 m/sec.; and in latitude 60° from 42° to 52.7° angle with similar wind speed. In similar latitudes the wind factor also decreases from 0.0317 at velocity 5 cm/sec to 0.0266 at 20 m/sec.; and from 0.0273 to 0.0228 respectively. Hence it is concluded that higher the velocity of wind, greater will be the angle of deflection. This wind factor according to Ekman remains 0.025 at 15° latitude and 0.0136 in 60° latitude; while Rossby says that the wind factor itself is a variable element depending on the depth at which wind current is measured, i.e., at depth it gives greater value.

We have seen above the effect of wind friction in a homogeneous water. But in the oceans density normally increases with depth. Hence the rate of penetration of wind current towards depth would depend on the changes of vertical density (by influencing eddy viscosity). If the upper layer is made homogeneous by cooling and is of considerable thickness, the wind current would reach its normal state very soon. Where there is a light surface layer, the mixing by wind current would produce a top homogeneous layer and due to stable lower boundary, the increase of this homogeneous layer is slower. Hence the penetration of the wind current depends on the thickness of the upper homogeneous layer. In middle and high latitudes, wind current reaches final stage more rapidly in winter than in summer.

A further analysis of the velocity of the wind current would reveal that the velocity at the bottom of the shallow seas is absolutely zero. This shows that the velocity of the current depends on the depth of the ocean. The surface records highest velocity and it decreases rapidly with the increasing depth. As already noted, the velocity of the current also depends upon the wind stress and the latitude.

In the open sea, where less varying factors influence the currents, the velocity varies inversely as the square root of the sine of the latitude.¹

The wind systems over the oceans, apart from maintaining a current, create convergences and divergences in the sea water. In the northern hemisphere where wind blows along a coast line in a manner that the coast is on the right side, the light water is accumulated along it. The current direction would not be 45° to the wind direction but just parallel to it. This is known as pure wind current and shows convergence along the coast of light surface water. Similarly, when wind blows parallel to the coast with the land on the left side, light surface water is transported away and cold and dense water upwells along the coast and moves in the direction of the wind. The idea of upwelling was first suggested by Thorade and developed by McEwen. Recent investigations also prove that the upwelling is only from the depth of 200 to 300 m. and not from the deep bottom. Hence an action of the wind is only overturning of the layer. This action is also found in areas in which north-east wind blows along the western coasts of the continent. E. Palmen (1930) found that in the Gulf of Finland persistent east wind causes a concentration of the lighter water against the north coast and a regular west wind concentrates lighter water along the south coast.

Observations have been made along the Californian coast which show a reversal of the current under the stress of the prevailing winds. Further, we see that just similar to the circulation of the atmosphere, the water circulation is also cyclonic and anti-cyclonic. In the North Atlantic a great cyclonic gyral round the Sargasso Sea consists of the North Equatorial current, the Antilles, the Florida currents, the Gulf Stream, the North Atlantic current and the Canaries current, formed by the trade and the westerly winds.

Disturbance of the level of ocean is also marked by the action of wind. E. Palmen (1932), E. Laurila and R. H. Corkan (1949) studied the disturbances of the sea level (surface gradient) in the Baltic and the North Sea. During stormy days the surface gradient is also rough in the North Sea and during the time when south wind blows (13 m/sec.) the difference in the level between the Wash and Danish coast, nearly over a distance of 550 km., was 91.5 cm.

Piling action of the wind. A constant and perennial wind blowing in one direction causes the piling of the sea water along a land barrier or a partially enclosed sea. The distribution of the water mass does not adjust according to the winds present above it, but is governed by the water mass carried into that region by the action of wind. For example, the high salinity and temperature of the water mass of the Gulf of Mexico and the Caribbean is due to flowing in of the North Equatorial current. Here a piling action takes place, as Parr has suggested, in front of the narrow Yucatan channel under the stress exerted on the coast by the prevailing easterly winds.

This idea was further examined by Sverdrup who found that the action of piling is under the force of the wind moving at 10 m/sec. Hence

¹ Marmer, *The Sea*, p. 262.

the sea level here is maintained higher than that along the U. S. coast towards the Atlantic. At Cedar Keys, off the south-west tip of Florida, the average sea level is 19 cm. higher than the average sea level at St. Augustine (Florida) on the east coast. Montgomery states that this accounts for the major part of the energy of Florida current.

On the basis of computations Wust found that 26 million $\text{m}^3/\text{sec.}$ of water is transported through the strait of Florida. This could give an idea of excess of water found in the Gulf of Mexico. On the open coasts, where shallow water extends to appreciable distance, similar piling up of water may take place during storms, as found in Galveston in 1900 during a hurricane. In the Indian Ocean similar piling up is noted along the Somali coast of Africa, and along the East Indies under the stress of trade winds. According to Montgomery and Palmen, this piling of light and warm water along western boundary of oceans amounts to about 150 m. in the North Atlantic and 300 m. in the North Pacific. The slope is from west to east and it decreases with the depth. In the Atlantic the slope is 3.8×10^{-8} and in the Pacific it is 4.5×10^{-8} . Hence the action of the piling up of water is found mostly where converging winds are found, which result in the formation of a slope current and give speed and momentum to such big currents as the Gulf Stream. Equatorial counter current, says Palmen, is the result of the accumulation of water on the west margin of the oceans by North and South Equatorial currents. To maintain the level, a slope current flows in the opposite direction (to the east) in between these currents.

The above study about the winds in relation to the currents shows that the circulation in the North Atlantic and the Pacific is dominated by south-west winds and the trade winds. One of the major currents is seen to correspond with the wind belts. In the southern ocean, the effect of wind is also striking. The westerlies flow in middle latitudes with considerable force (due to absence of land) and propel the surface water in the form of west wind drift round the earth. Other currents to some extent also follow the wind circulation.

(c) *Precipitation.* The excess of precipitation over oceans, in some areas, would disturb the level and result in the slope currents to equalise it. Equatorial regions record highest rainfall, hence the level is slightly higher in relation to the middle latitudes. Thus the resulting currents flow northwards and southwards. Again, the greater amount of rainfall in Equatorial region also lowers the salinity and the mass, hence the surface water becomes lighter and flows north and south. Just opposite to this, in regions of lower precipitation the level is abnormally low, water is more saline and dense; thus a sub-surface current flows outward, whereas a surface current moves in from the areas of excessive rainfall.

(d) *Nature of evaporation and insolation.* Differences in the distribution of insolation and amount of evaporation over the oceans lead to current formation. The temperature distribution would reveal the amount of radiation and insolation received by the oceans. In general it is noted that lower latitudes receive greater amount of radiation than the higher latitudes. If the amount of evaporation is also included then this fact changes the situation. In spite of high insolation, less amount of evapo-

ration makes the surface water lighter due to less salinity and less density, and water moves in the direction of areas of high density on the surface. However, in most of the inland and enclosed seas of middle latitudes, the evaporation and the amount of radiation both are increased. Hence salinity and density are also increased, the level of the sea is lowered and the surface current of light water enters that area from outside. In the open seas also higher evaporation over precipitation increases salinity, and thus density is comparatively higher. Again, in the northern latitudes excess of rainfall through the westerlies and less amount of evaporation lowers the density and the salinity of the surface water. Here, again, the surface movement starts towards comparatively denser areas. Thus in general we would find waters of the equatorial region moving towards the temperate region; similarly, polar waters with excess of fresh water, due to lesser evaporation and less insolation, also move towards the temperate latitudes whereas in return the denser water flows at the sub-surface. In the enclosed seas and bays, the effect of evaporation and insolation is clearly visible. Because of an excess of evaporation over precipitation the level of the Mediterranean tends to fall and hence there is an inflow of current from the Atlantic.

FACTORS WITHIN THE SEA WATER OR SUB-OCEANIC CAUSES

(a) *Pressure gradient.* The variation in the pressure gradient within the ocean may also result in an internal disturbance. The surface of the sea over which the pressure is uniform or all points on which same pressure is found is known as 'isobaric surface'. Within the sea, pressure from all sides acts over a particle, hence the amount of pressure on any small element can be computed from the depth at which it is found, and on the co-efficient of compressibility of sea water. Generally, as pressure increases downwards, the isobaric surfaces are parallel to the sea-level. Further, the isosteric surface is that on which all points have equal specific volume. If the temperature of the sea is same everywhere, isosteric surface would be parallel to the sea level. Due to the decrease of temperature from equator to poles and from surface to bottom, the isosteric surface will not be parallel to the sea level or to isobaric surface, but would cut across it, because the pressure and specific volume increases with depth. Thus it is deduced that due to the forces inside the sea water and the pressure of the sea water, the pressure automatically increases downward. Hence, surface water is always of less density as compared to that of the bottom water. Due to these differences vertical and horizontal currents are formed.

(b) *Temperature Differences.* Temperature difference in the sea is the most important factor generating currents in sea water. In order to understand the thermo-dynamics of the ocean current, a few facts regarding the ocean water must be understood.

The ocean, like atmosphere, is a heat engine in which solar energy is taken in at certain places and given out at other places. This creates temperature differences which maintain the motion, which in its turn brings equal distribution of temperature. The temperature of the sea surface, as noted before, is raised differently at different latitudes by the process of absorption of radiation, or by conduction of heat from a

warmer atmosphere or, though small in amount, by dissipation of kinetic energy, and by friction of currents against the bottom of the sea. Consequently, the reduction of temperature is possible by radiation from the sea, by evaporation, and by direct conduction of heat to a cooler atmosphere.

Hence the result of this latitudinal variation would be a general diminution of temperature from the equatorial to the polar regions. The higher temperature in a region means greater expansion. If other elements are not included, then water would expand towards colder areas on the surface. To balance the loss of water at the equator or in the region of higher temperature, near the poles cold water sinks such as near Antarctic convergence and moves towards the equator as a sub-surface current. These two currents—poleward surface and equatorward sub-surface—bring about other currents, i.e. a vertical upward current at the Equator which actually balances the water loss at surface and a vertical downward current at polar areas to mark divergence or sinking. Thus a complete circulation is maintained in the ocean, which preserves the continuity of the current. These resulting currents across the parallels, e.g. the Kuroshio and the Gulf Stream, maintain the balance of temperature on the surface.

Variations are marked in this temperature difference circulation on the surface or at sub-surface due to other important controlling factors. In non-polar regions of the oceans, there is often a layer of water in which the temperature decreases with increasing depth at a much greater rate than in the layer either above or below it. This is known as 'Thermocline-layer'. Between the Gulf Stream and the east coast of U.S.A., the depth of the thermocline-layer is about 250 m. while in the Sargasso Sea the corresponding depth is about 750 m. The existence of this layer was marked by 'Challenger' in 1873 and presented in a graph by T. M. Tizard (1884). Further, the temperature decreases from the surface downwards but sometimes the occurrence of strong winds creates mixing or an inflow of dense saline water from an enclosed sea, creating an increase in the sea temperature for some depth. This results into local variations in the movement of currents.

(c) *Salinity*. Salinity is considered to be one of the causes of the currents. In a basin, if the northern part records lesser salinity than that of the southern, the density will also vary and the motion of the water will be somewhat like this: at the south end sinking of dense saline water would take place and that would move as a sub-surface current to the north end and upwelling of less saline light water at the north end would result in a surface current towards south. Thus a complete circulation including surface and sub-surface currents would take place. There will also be a resulting slope of the sea surface from south to north.

Similarly, the movement of water is recorded in relation to the partially enclosed seas. In enclosed seas, such as the Mediterranean and Red Sea, the temperature and evaporation is higher which results in considerably higher salinity and higher density. This is accompanied with the less influx of fresh water. As a result the level of these enclosed seas tends to be slightly lower and the pressure slightly higher than in the

open ocean. This results in two types of currents near the straits, i. e. the dense saline water sinking downwards, and flowing on the bottom of the inland sea towards the open ocean, and to cover this loss of water a less saline surface current from the open ocean moves towards the enclosed seas. Such surface and sub-surface currents exist between Mediterranean and the Atlantic across Gibraltar Strait and between the Red Sea and the Indian Ocean across the Bab el Mañdeb Strait.

In other enclosed seas such as the Baltic, the flow of fresh water by rivers raises the level and lowers the salinity. Here the surface water which is less saline moves outward into the North Sea, whereas a bottom current of comparatively higher salinity is moving from North Sea to the Baltic Sea. Similarly, low saline water of the Black Sea flows as a surface current into the Mediterranean. The East Greenland current is also a similar current which carries water of low salinity and low temperature towards the high saline areas.

(d) *Density*. Density, being the sum total of temperature, pressure and salinity, directly controls the current. But as this factor depends on a variety of reactions of the above factors, a most complicated pattern of density currents is formed in the oceans.

As a general rule, we find that the temperature governs the density variations, i.e. higher the temperature, lower will be the density (greater expansion of water), and *vice versa*. Hence this shows a decrease in the density of water from the pole to equator. As a result, low density surface current would flow from regions of higher temperature into regions of lower temperature, whereas a sub-surface dense water would flow from cold to warm regions.

However, apart from temperature, salinity is also an important factor in density determination. So in regions of similar temperature conditions, we find density variations due to difference in salinity. High temperature and low salinity record low density, but high temperature with high salinity have greater density. Similarly, low saline polar waters are less dense as compared to highly saline polar waters. Due to the above fact, in the middle latitude enclosed seas with high salinity record greater density as compared to the open oceans. Hence, surface currents of low density move from open oceans in the enclosed seas.

The density variations are also found in the depth. Though the salinity conditions remain almost the same in all the oceans after a certain depth, yet a decrease of temperature is found. This results in greater density of sea water in the lower part, as compared to the surface water.

Again, due to the increase of pressure near the bottom, the density also increases from surface towards the depth. The general tendency would be a lighter water on the surface and denser water at depths. Hence, the moment the surface water attains higher density than the surrounding water as a result of increase of evaporation, salinity etc. or by mixing of cold polar waters with warm saline waters, it sinks towards the bottom and spreads in the layers of similar density. The descending vertical currents in the ocean can penetrate to any depth, depending upon the stratification

of the water. This stratification is strengthened when a mass of water sinks downward until it meets waters of equal density. Where vertical currents are thus active, a homogeneous layer is formed at the surface. If light surface water is driven away by winds, dense sub-surface waters would upwell on the surface. In this case dense water is formed on the surface.

In spite of this complicated form, the general rule remains the same: the low density water being lighter expands and flows as a surface current towards highly dense water regions, and a sub-surface current of higher density flows from regions of greater density to lesser density.

The distribution of the currents is governed by the density factor is such that low density water of equatorial regions moves towards the poles. Many branches of low saline water shoot off into partially enclosed seas of highly dense waters. Polar currents move towards low latitudes but no sooner they get mixed with warm saline waters, they become dense and sink downward. Hence an under-current of dense bottom water moves towards the equator to compensate for the loss. Dense water of Antarctic convergence could be found moving in the sub-surface towards the equator.

(c) *Melting of ice.* It should be noted that a very prominent part is played by the melting ice in the formation of current. Otto Pettersson was first to observe this effect and concluded that due to ice-melting, the water level is raised higher and the salinity of the water decreases. Hence the currents move outwards from such regions. The East Greenland current is supposed to be such a current.

FACTORS MODIFYING OCEAN CURRENTS

(a) *Direction and shape of the coast line.* It is one of the important factors modifying the direction of the current. The South Equatorial current is dammed by the presence of the South American continent but due to its projecting nose at Cape San Roque this current is bifurcated into two: one part enters into the Caribbean Sea moving along the northern coast of South America and the other moves to the south following the direction of the coast of Brazil. Similar deflections are found on the western parts of equatorial oceanic regions where piling up of water takes place. In the Indian Ocean also the monsoon drift closely follows the form of the Indian coast line. In the Pacific Ocean the islands obstruct the flow of the currents and govern their directions.

(b) *Seasonal variations.* Almost everywhere in the ocean seasonal variations in direction and in volume of the current systems are found. The currents of the Indian Ocean show a marked change in their direction. During north-east monsoons in winter, the direction of the monsoon drift is from east to west along the coast. But reversed direction is noted in summers when south-west monsoon drags the current in the north-east direction. Consequently changes are also noted in the Equatorial counter current and north Equatorial current of the Indian Ocean. The former appears only during winter months, and the latter only in summers.

In the Atlantic Ocean similar changes are found in the Equatorial region. In the northern summers the axis of the south Equatorial current is near 2° S. Hence most of the water moves in the northern hemisphere and the counter current is quite clear. The whole system shifts to south during northern winters and the axis of the south equatorial current lies at 5° S. Then the counter current also narrows down.

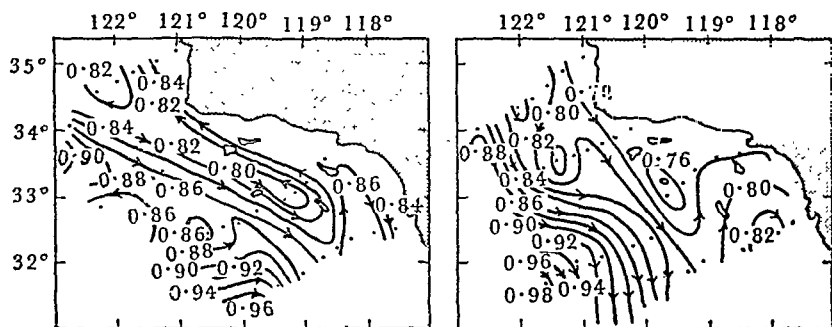


Fig. 87. (Left). Geopotential topography of sea surface off southern California relative to the 500 decibar surface in February, 1938, after a period with westerly or south-westerly variable winds.

(Right). Topography and corresponding currents in June after a period with prevailing north-westerly winds.

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Fig. 87 demonstrates the effect of winds from different directions off the coast of southern California. During the absence of the wind, a southerly or south-east flow of the main Californian current is found along the coast. The current is usually dragged away from the coast line due to the presence of winds. Hence another coastal current emerges between this current and the coast line which changes its direction according to the deviation in the wind direction. During February westerly winds flow from the south-west direction, thus the light surface water flowing far from the coast is again deflected inshore, and a current is flowing from south to north. It is separated from the main current by a trough line representing divergence. Contrary to this, in June north-easterly trade winds blow in this region which throws the light surface water away from the coast to a distance of about 150 km. which later flows southward along the main current. But here also a boundary line appears between these two currents representing comparatively light offshore water on the left and dense upwelled water on the right. Thus a wind controlled reversal in the direction of the coastal current is found along the Californian shores.

In the open ocean, like North Atlantic, the gyral of ocean currents also shows a periodicity in the flow of water into the northern marginal seas. Normally the North Sea records 34.5% salinity, but 35% salinity is also found due to the influx from the Gulf Stream during March to

November, when the Gulf Stream system shifts to north. Moreover, after November, the Atlantic gyral moves to south. Therefore currents do not extend further northward and due to frequent changes in the direction of the winds less influx is recorded. Same periodicity is found in the other marginal seas along the Atlantic.

Another area where seasonal variation of wind is found to affect the current is on the west coast of central America and Mexico. During summers when the Equatorial counter current strikes the coast it moves northward along the coast line and joins the north equatorial current. Hence a northerly flowing south-east monsoon drift is found. In the month of January under the stress of the north-east winds the North Equatorial current after striking coast sends a branch along the Mexican coast towards the south, which further flows into south equatorial current. Thus the whole system is changed and shifted to the south.

(c) *Bottom topography.* The nature of the bottom topography to some extent modifies the currents on the surface as well as on the bottom of the sea. Ekman has examined the above fact by taking into account the rotation of the earth. According to him, in low latitudes the currents tend to flow east-west, independent of the slope of the bottom, but in middle and high latitudes the currents tend to follow the bottom contours.

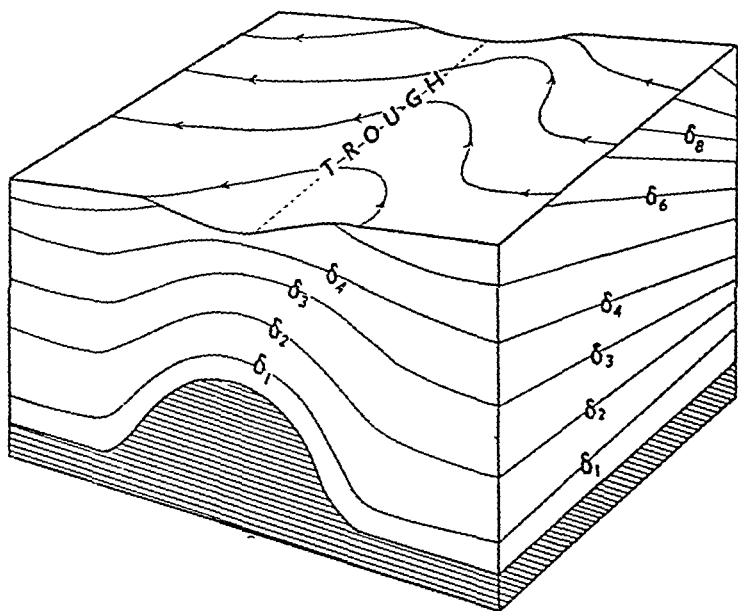


Fig. 88. Perspective diagram showing the deformation of the sea surface when a relative current reaching nearly to the bottom crosses a submarine ridge.

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The curvature or the deflection observed in the surface current as a result of bottom barrier would be greatest where the change in the slope is greatest. In a homogeneous layer, the presence of the slope current within which the velocities are independent of depth, except within a layer, are influenced by bottom friction. But in a non-homogeneous water, the isosteric surfaces would be horizontal at bottom and sloping above in such a manner that looking towards the direction of flow the water of greatest specific volume (lowest density) is to the right, and of least specific volume is to the left. When there is a submarine ridge under the water mass, the surface would rise, and the distribution of mass is altered in such a way that the surfaces slope upward when approaching the ridge and downwards after passing the ridge. The resulting current over the surface would also swell at the ridge and a low pressure trough would develop over it as shown in Fig. 88.

Thus, in general, a deep current is deflected from its straight course when crossing a ridge, the deflection being to the right in the northern hemisphere, and to the left in the southern hemisphere. The maximum deflection in this case is directly over the ridge. An important example is afforded by the Gulf Stream Drift crossing at the Wyville-Thompson ridge, where shallowing of the current and notable variations are marked as shown in Fig. 89. Here only at one place is the sea deep enough to

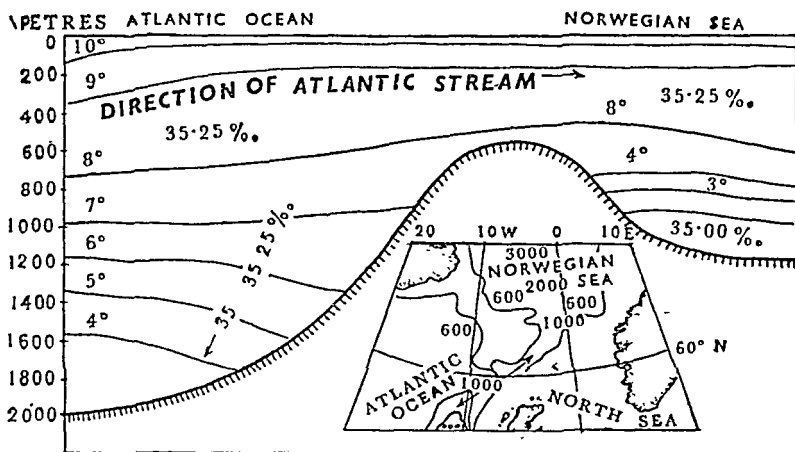


Fig. 89. A diagrammatic section across the Wyville-Thompson Shetland-Faeroe ridge. The horizontal scale is much smaller than the vertical one. The inset is a sketch chart of the area. The soundings are in metres.

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allow the current to move north-east, that is in the channel between Shetland and the Faeroe islands. At other places shoaling restricts the north-east drift of the upper layer of the ocean. A remarkable change in the temperature and salinity are marked on either side of the ridge. Fig. 89 shows how waters at varying depths of 2000m or 1000m in the Atlantic and the Norwegian Ocean are affected differently due to the

barrier. The Norwegian deep water is not affected by north-east Gulf current, therefore comparatively low temperatures are found at the bottom. A similar example is found when the Antarctic circumpolar current crosses the submarine ridge between South Orkney island and Falkland. One branch of the current flows to the south of southern Georgia following the bottom contours, but another part crosses the ridge and is deflected sharply to the left.

South and south-west of New Zealand, the Antarctic circumpolar current crosses the Macquarie Ridge, bending sharply north and south between 180° - 150° W. Here also a sharp bend towards the left is seen in the current after which it moves towards the right.

The observations of Wust (1940) and Neumann regarding the Altair dome in the North Atlantic show that just above this ridge the current is diverted and widened, and a cyclonic eddy develops over it.

The mid-Atlantic ridge extending from north to south is also supposed to influence the direction of the Atlantic currents. The most marked deflection is seen when the north Equatorial current crosses the central ridge and is deflected towards the right. In those areas where many islands and continental shelves form the shallow bottom, currents are also not well established and are directed according to the bottom topography.

ACTUAL PATTERN OF THE CURRENTS

After studying the ideas on the dynamics of the currents of the ocean, it is necessary to analyse a general pattern of the currents.

According to Schott, the ocean water should no longer be described as moving clockwise in the northern hemisphere or counter-clockwise in the southern hemisphere. Fundamentally, the currents are related to the direction of the prevailing winds, moving a little right in the northern hemisphere and left in the southern hemisphere as explained in Fig. 90.

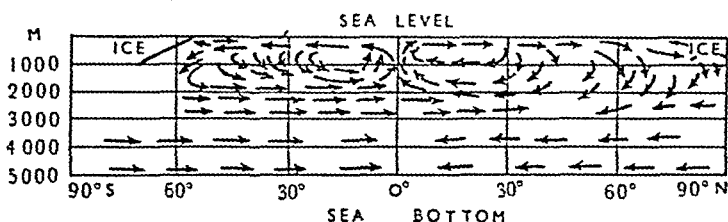


Fig. 90. Current relationship to the prevailing winds (After Otto Krummel).
(By permission from the Geographical Review, Vol. 37).

In the Equatorial latitudes under the stress of the north-east and south-east trade winds, Equatorial currents move towards the west. In between these two, a compensating current moves towards east. In the middle latitudes, under the prevailing westerly winds, the currents of the lower latitudes are deflected to the south-east and north-east direction,

thus forming major currents of the ocean. Further, eastward the currents due to the rotation of the earth are deflected to the south in the form of cold currents and mix in the Equatorial waters. One branch of this central north-east and south-east current moves into the colder seas where it loses its characteristics. Under the influence of polar easterly winds the Labrador or Falkland currents move into the warm latitudes on the eastern coast of the continents. Thus gyres are found in northern and southern parts of all the oceans. In the central portion, though minor eddies develop, yet there is no marked movement of the current. A vertical cross section of the currents shows the complicated movement in the ocean.

Most of the currents of the oceans depend and are governed by the theoretical pattern of circulation which adheres to the following rules:

(1) Warm currents move towards the cold seas, and cool currents move towards the warm oceans.

(2) Cold dense upwelled waters are found in the middle latitude (trade belt) on the western shores of the continents.

(3) From the colder seas the cold waters of lesser density move into warmer oceans along the eastern coasts of higher latitudes.

(4) In the lower latitudes, warm currents are found on the eastern shores and the cold on the western shores, whereas in the higher latitudes, warm currents flow along the western shores and cold currents on the eastern shores.

(5) Further, convergences and divergences in the oceans also control the currents. In each hemisphere there are three different water masses and two convergences, namely, sub-tropical and sub-polar convergence.

(6) The currents and their nature vary according to the seasonal changes in the year.

Chapter 14 | CURRENTS OF ATLANTIC OCEAN

The currents of Atlantic Ocean have a well-defined pattern of circulation. There is a clear division of the circulatory system into the currents of the North Atlantic and those of the South Atlantic. In the equatorial part of the Atlantic as well as in the seas adjacent to the North Atlantic also there is a well developed system of currents.

EQUATORIAL PART

North Equatorial Current. The two equatorial currents form the backbone of the system of currents present in the Atlantic Ocean. The Northern Equatorial current is comparatively less constant in extent and strength. It is situated between $0-10^{\circ}$ N latitudes mainly. Further north, north of 20° N latitude its intensity decreases and it passes into an extensive region of weak and variable currents with frequent motionless areas. The movement of water is from the easterly part of the ocean where it drives the water from the cold Canaries current along the African coast. The Equatorial current attains its main characteristics only after leaving the coast of Africa where cold water is upwelling, and then remains throughout a warm and saline water mass.

This current was first described by Findlay (1853) who states that it does not follow an absolutely straight course but covers different areas of the ocean at different times of the year. Schumacher (1940) points out that north of 15° N, the Equatorial current bends to the north (to the right) when approaching the Mid-Atlantic ridge and to the south (to the left) after having passed the ridge. The deflection on the surface is just above mid-Atlantic ridge though it lies 3000 m. below. The observations reveal that during most of the months of the year, north of 15° N the intensity of Equatorial water mass between the surface and 2000 m. depth is influenced by this ridge.

Further west, the North Equatorial current is joined by a branch of South Equatorial current as a result of convergence and the latter carries slightly different water mass to the north. This line of convergence from about 20° W, 4° N to 50° W, 11° N develops in winter months when the equatorial counter current is weak. It is here that the North Equatorial current diverts to the north due to the land barrier of the South American coast and is split up into two branches. The first branch is the Antilles current which flows east of the West Indies islands, recurring continually to the north and east to form the Sargasso Sea eddy as shown in Fig. 91. It is suggested that the deflection is

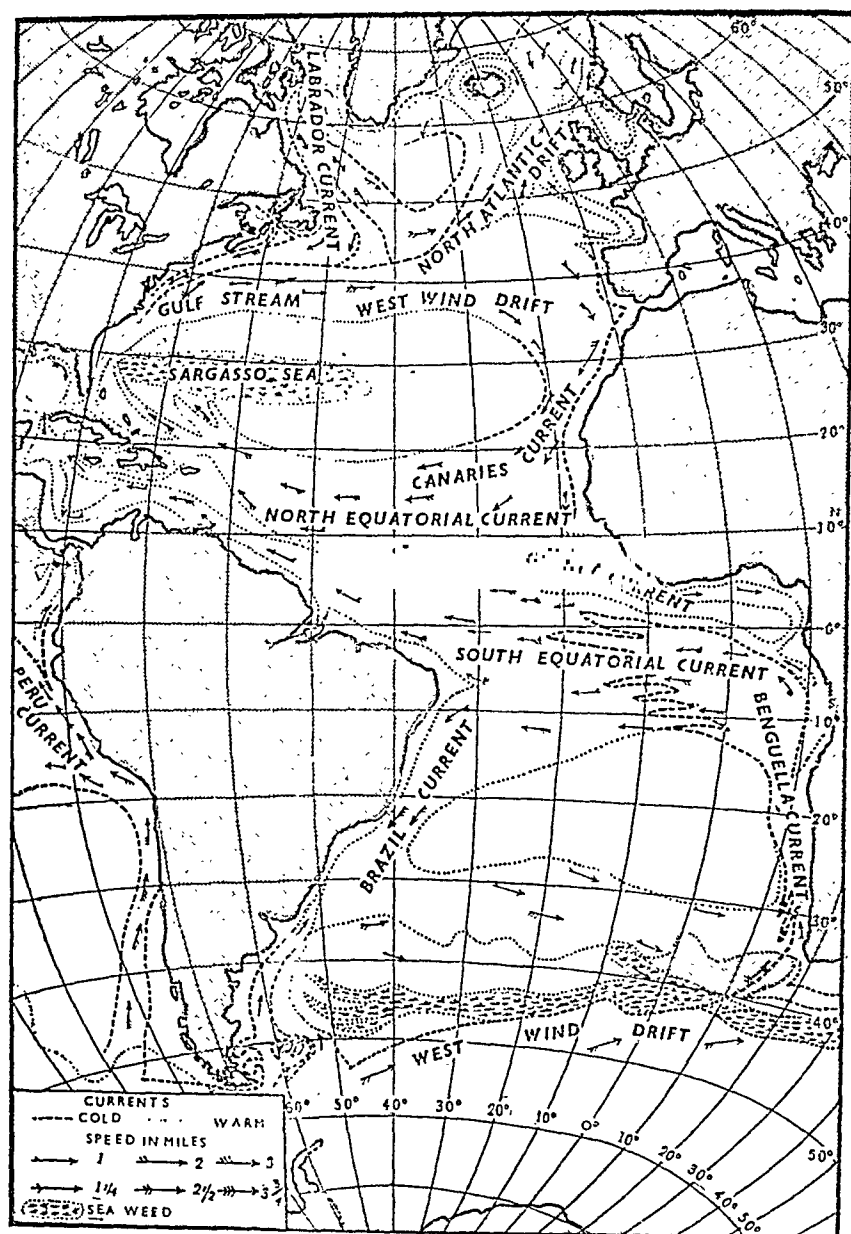


Fig. 91. Surface Currents of the Atlantic Ocean.

partially due to the land barrier, and mostly because of the deflection force of earth's rotation. The second branch of the current is diverted into the Caribbean Sea and extends up to the Yucatan channel. Further, the branch enters the Gulf of Mexico where it is not distinguished by any name. The general movement of the water is northwards. There is a vast difference in the waters of the two north equatorial branches, i.e. the Antilles current is similar to the Sargasso Sea water and the Caribbean current gets mixed up with the water of the South Equatorial current.

The southern boundary of the North Equatorial current, between 20° and 25° W longitude varies from 60° N latitude in March and May to 12° N latitude in September. The velocity of the current is also variable from 5 to 30 sea miles per day. The greatest velocity of over 40 sea miles per day is recorded in the period extending from December to June. In the southern part, the speed is 15 nautical miles per day. The current velocity is also not similar in all the parts of the current. Along the African coast the drift is weaker, whereas off the West Indies it is much stronger.

South-equatorial current. This current, flowing south of Equator within 0° - 20° S latitude in between the coast of Africa and South America, is the northern continuation of Benguela current. It is stronger and more constant and of greater extent than the North Equatorial current. The current eastward of 30° W longitude and southward to 15° S latitude is as strong as a permanent stream. At the meridian of Greenwich, the northern boundary of the stream corresponds to 1° to $1\frac{1}{2}^{\circ}$ N latitude, whereas in the west in some regions it is about 3° to 4° N latitudes. This position continues till 30° W longitude. At this place the projecting nose of Cape San Roque divides the South Equatorial current into two parts. The north-west branch joins the North Equatorial current near Trinidad and the other one turns southward and forms the Brazil current.

The velocity of the South Equatorial current varies in different regions. Near about Cape San Roque, the velocity is between 30-60 sea miles per day. It also varies according to seasons and the maximum velocity of 100 miles per day is found during northern summers. There are other variations in the nature of the South Equatorial current, i.e., the surface waters between 10° - 25° W longitude have a temperature 3° - 4° C colder in the month of August than in February. Hence a cold zone is found just near the equator.

Both these Equatorial currents of the Atlantic Ocean originated under the stress of trade winds. In the northern part, the north-east trade wind blows with 5 to 6 strength (on Beaufort's scale) in February and with still greater speed in winter, though slight variations in direction are found, e.g. north of Equator, north and north-east near the eastern part, north-east in the centre and east north-east near Antilles. The current thus originated also moves according to the wind direction and exhibits N 81° W direction of the current as against S 51° E of that of the wind. The deviation amounts to 30° and is attributed to the earth's rotation. In the southern part of the ocean, the trade wind is not so strong (4 on Beaufort's scale). Between 5° - 10° S the direction of the wind

is south-west, near Ascension south south-east and on the African coast it is south and south-west and attains the maximum during northern summers. The current also changes according to the varying wind direction. Further, changes in these streams occur due to the shifting of the wind belts. During northern summers, the whole system moves northward, and south equatorial current actually crosses the equator near 10° W longitude and extends up to 6° or 7° N latitude as shown in Fig 92.

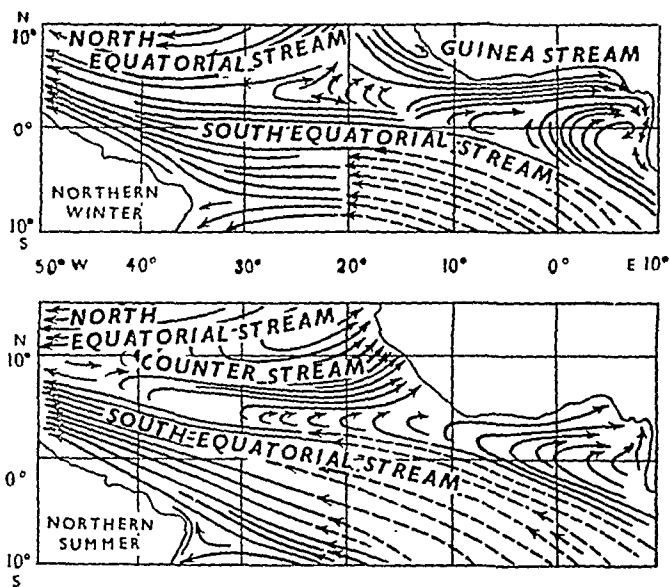


Fig. 92. Upper : The Atlantic Equatorial Stream circulation in the northern winter.

Lower: The same during July and September.

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Equatorial counter current. Similar to that of the Pacific, here a typical calm zone exists near the equator in which the counter current moves towards the east. But here the current is neither so well developed nor it is too strong due to the shape and the width of the ocean. The counter current is only well marked in the eastern part, whereas in the west it slowly disappears and mixes with the north and south equatorial currents due to the stress of trade winds and the shape of the continents.

The counter current is known as the Guinea Stream in the east whose boundary is not fixed but changes according to the nature of the winds. During northern winters, its axis is two or three degrees north of the equator, whereas in July and September the current moves north and is much stronger. Therefore its axis lies about 7° N and extends up to 40° W. The average extension of the current along the African coast

between Cape Roxo and the Bight of Biafra is upto 3° N and 23° W. The velocity is estimated to be 18 sea miles per day with a maxima of 40 to 50 miles in certain areas. The temperature of this current is higher than Equatorial current, except in August due to the excess of rainfall. The density is also comparatively lesser due to the same reason. Cooler water in the current occurs between 4° - 7° W longitude, i.e. off the Cape Three points. Hence warmer breeze flowing over this current produces fogs and makes navigation dangerous.

Many causes have been put forth to prove the occurrence of this current in the Atlantic. According to some, during northern summers south-west monsoon develops in the zone of calm, with the average strength of 3.66 (on the Beaufort's scale) driving sea water at a speed of 12.3 sea miles per day. But actual observation shows the movement nearly 20 sea miles per day. Hence wind accounts only for $3/5$ velocity of the current. But the current is also found during winter season when monsoon completely disappears. Therefore the origin could not be attributed to the action of the wind alone.

Thus another idea develops about its origin which considers the current as "compensation current" resulting due to the creation of slope from west to east, as a result of the convergence of two great equatorial currents, and the piling up of water along the western boundary of the ocean on the South American coast. The accumulation increases the thickness of the homogeneous surface layer from 40 m in the east to 140 m in the west. The ascent or piling up is under the strong action of the trade winds. Montgomery states that the dynamic height of the sea surface is 14 dyne/cm greater in the west than in the east or the slope amounts to about 4 cm. per 1000 km. Therefore, to equalise the level of the sea a shallow counter current rises, and there is also an observed inward movement of the equatorial streams towards the axis of the counter current which enters the Gulf of Guinea.

Another factor which accounts for the origin is the location of the discontinuity layer between the counter current and the neighbouring

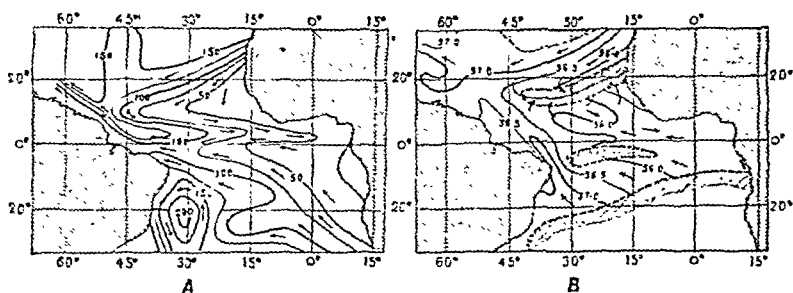


Fig. 93. (A) Topography of the discontinuity surface in the equatorial region of the Atlantic shown by depth contours in metres and corresponding currents.

(B) Salinity in the layer of maximum salinity below the discontinuity layer and assumed currents. Regions without salinity maximum shaded (After Defant).

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waters. In the equatorial part, the water masses below 50 to 150 m depth are mostly separated from the surface waters by a layer known as discontinuity layer, in which density increases rapidly with depth as shown in Fig. 93. This layer takes its birth due to absorption of solar insolation and mixing of low temperature sub-surface water from higher latitudes.

Due to greater mixing, the difference between warm surface and cold sub-surface layers is concentrated in a thin discontinuity layer which gradually develops a stable stratification. Hence, further mixing is checked and additional insolation is used for evaporation or transporting energy in a current. In any area the thickness of the upper warm layer depends on the intensity of mixing as well as on the character of the circulation in the above layer. If there are currents on the surface, the discontinuity layer is not horizontal.

The observations of Defant in the Atlantic proved that in the northern hemisphere if the discontinuity surface is sloping, the flow of the water is such that the sinking of the surface takes place on the right. In the southern hemisphere, the surface sinks to the left.

The origin of the equatorial counter current is due to the presence of discontinuity layer. A cross section across the Atlantic from north to south shows how discontinuity surface rises towards the equator from the southern hemisphere and falls near about 2° N latitude. This region corresponds with the south equatorial current. Again, the surface rises near 3° — 8° N latitude and forms the region of the counter current. A further increase in the depth denotes the occurrence of north equatorial current.

According to the observations of Montgomery and Palmen, the counter current is subject to greater friction and retardation at its boundaries with the north and south equatorial currents as a result of lateral mixing. This frictional stress is directed opposite to the horizontal stress exerted by the trade winds. Defant found the formation of cell circulation due to vertical mixing though lateral mixing is not excluded.

Fig. 93 shows that the northern boundary of the counter current lies at ascending current, whereas the southern boundary lies near the descending region of the currents.

NORTH ATLANTIC

The currents of North Atlantic Ocean have developed a complete system in a clockwise direction, leaving a central part known as Sargasso Sea region, as shown in Fig. 91.

Gulf Stream system. Named by Iselin, this system includes the north-east moving waters of the Atlantic Ocean extending from 20° N along the eastern coast of America up to 60° N on the western shore of Europe. It is perhaps the most important current system of the Atlantic. It has a widespread influence over the region. The system includes (a) Florida current from the strait of Florida to Cape Hatteras; (b) Gulf Stream from Cape Hatteras to the Grand Bank at 45° W longitude; (c) North Atlantic current east of Grand Bank.

(a) *Florida current.* The Florida current is the northward continuation of the north equatorial current which passes through the Yucatan channel into the Gulf of Mexico. Hence it carries most of the characteristics of the equatorial water mass. The current, after flowing past the Yucatan channel, enters the Gulf of Mexico. The greater part of it bends sharply towards the right and takes the shortest route. Further, it moves with great velocity through the strait of Florida into the open sea.

The energy of the Florida current is derived from the trade winds moving at the rate of 10 m/sec. which pile up the water in front of the narrow Yucatan channel. This action is further intensified by the circular shape of the Gulf of Mexico and the southward projection of the Florida peninsula, which further restricts the free movement and enhances the piling up action of water. The passage east of the Florida strait is only 5 miles wide and 60 fathoms deep. Hence Montgomery states that the resultant velocity of the frictionless current through the strait of Florida should be 193 cm/sec., that is, comparatively higher than the average velocity in the central part. Marmer states that near Havana the velocity is $2\frac{1}{2}$ knots. Here in between Florida, Keys and Cuba, the width of the channel is 95 nautical miles and the depth averages about 100 fathoms. In the north of the strait of Florida, west of Bahamas, the channel further narrows down; therefore the surface velocity increases to $3\frac{1}{2}$ knots but at 130 fathoms it is only $2\frac{1}{2}$ knots. The yearly average of the velocity comes down to about 72 miles per day, but in January and June it is between 100-120 miles per day. During the time of northerly wind the current is strengthened, but during the period of depression over the Gulf the water rushes inside and the current flows against the north-east wind.

The following data give the average velocity met in this current at various places.

	Miles/per day
Yucatan strait east of Cantoy island	35
North of Havana	25
East of Fowey rock (Florida)	11
East of Jupiter Inlet and Fort (Florida)	19
S. E. of Cape Hatteras	38

Many variations are also noted in this current regarding its direction and strength. According to Pillsbury, the periodic variations are according to the declination of the moon. The greater is the declination, the more is the current bent to the left and it broadens and decreases in temperature, whereas during lesser declination it bends to the right, narrows down and increases in temperature. Most of the observations regarding temperature and salinity characteristics were done by J. E. Pillsbury between 1885-1889 on 'Blake' expedition. The records exhibit that the current does not carry water colder than 6.5° C. until up to 33° N. At the surface the temperature and salinity is 75° F and 36‰ respectively.

Further, the amount of water that is transported through the strait of Florida, as computed by Wust, amounts to 26 mill. m^3 /sec. as an

average yearly flow. He calculated the speed in relation to temperature and salinity, as shown in Fig. 94. According to Wust 100 billion tons and according to Pillsbury 90 billion tons of water passes per hour through the Florida strait. This amount of water transported out of the strait is 1000 times the average discharge of Mississippi (660,000 cubic feet per second) and 500 times of its flood discharge (1,800,000 cubic feet per second). Just after the Florida strait, the channel widens and the current flows along the continental shelf. The depth is only 800 m.,

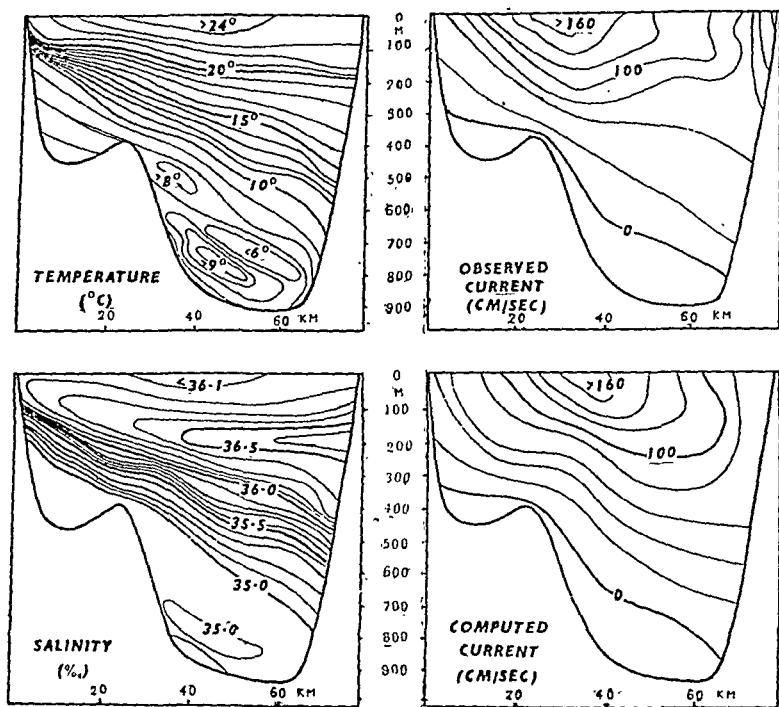


Fig. 94. Observed temperatures and salinities in the Straits of Florida (Left). Velocities of the current through the straits according to direct measurements and according to computations based on the distributions of temperature and salinity (Right)—After Wust).

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hence the current is comparatively shallower but it is clearly separated from the still and shallow waters of the coast. Further northwards, the current moves away from the coast. Near St. Augustine the current is 30 nautical miles far off the coast, and after 150 miles north of it the current flows 85 miles away from the coast. Near Cape Hatteras, it is again 10-20 miles off shore due to the eastward projection of the land. The width of the channel also varies from south to north according to the influx of the water from sideways. Near the strait, it is only 30 miles wide, but near Cape Canaveral its width is 60 miles and at

Charleston about 120 to 150 miles. This broadening of the current is mostly towards the east, while western edge corresponds to the 200m. contour line. Near about 30th north parallel the Antilles current, a branch of North Equatorial current, joins it and according to Wust it carries 12 mill. m³/sec. of water. According to Krummel (1911) it actually carries 2½ times of water and heat as compared to the Florida current. But Wust gives just the opposite opinion when he finds the Florida current bringing twice as much water and heat as that of the Antilles current. Iselin remarks that further increase in volume of the current is due to absorption of Sargasso water.

The origin of this current is attributed to many causes. According to Franklin, the Florida current is only a drift current, forced to move under the stress of trade winds. The whole Caribbean Sea is found under the stress of strong west moving winds which force the water to move out of the strait of Florida. Again, it is found that due to the action of the winds the water is piled up in the Gulf of Mexico. The consequent difference in the sea level is noted by Parr (on the basis of 'Atlantis' data), Sverdrup and Montgomery. According to them, between Cedar Keys off the south-west tip of Florida and St. Augustine on the east coast, the difference of level is found to be 19 cm. Hence the Florida current moves in the open sea to balance the sea level.

Another theory proposes the differences of density between the Gulf of Mexico and the neighbouring ocean as the cause of the origin of the current. The salinity in the Gulf is approximately 35‰ which is less than that of the surrounding ocean.

Further, a few investigators have also noted that during strong westerly winds a depression is formed north of 30° N latitude and may be taken as another cause of the origin of the current. In summer, the south and south-west wind in this section helps Florida current to move further.

(b) *Gulf Stream*. The discovery of this stream dates back to March 1513 when Ponce de Leon, while sailing to the West Indies, noticed the existence of a fast current. Later, Alaminos in the same year noted the wide extent of this current. In 1770, Benjamin Franklin, while writing about the delays in the communication between England and America, said that the Rhode-Island captains were acquainted with the Gulf Stream. In the words of Matthew Fontaine Maury (American Naval Officer), "There is a river in the ocean....The Gulf of Mexico is its fountain, and its mouth is in the Arctic Sea. Its current is more rapid than the Mississippi or the Amazon."¹

Thus enforced by the waters of the Antilles and the Florida current, the Gulf Stream, a comparatively broader but warm current, takes its shape off the Cape Hatteras. The current is distinctly separated from the Sargasso Sea to the right and the shallow water of the shelf on the left. The region on the left has lower salinity and temperature (4 to 10° C), making a boundary which is known as the "Cold Wall", and is well marked off Cape Hatteras.

¹ Quoted in Marmer, *The Sea*, p. 266.

The cold water along the eastern coast of U. S. A. is considered to be either the result of the drainage water from the land or the Gulf of St. Lawrence water deflected to the south along the coast. But few people think that it is due to the constant contact with the cold land in winter. Most people agree that due to westerly winds, which carry warm water off the coast, the Labrador water comes up to Cape Hatteras and upwells as a cold bottom water. The difference of temperature from coast to seaward within 220 feet amounts to 22° F.

However, the Gulf Stream continuously carries warm water into the colder latitudes. The Stream bends with the coast line but at 40th parallel the direction is almost to the east, due to the action of the westerlies and the deflective force of the earth rotation. Further northward it is divided into various bands of warm channels known as the delta of the Gulf Stream. The major north-easterly branch retains the name of Gulf Stream. As shown in Fig. 95, the Gulf Stream is a well defined stream affecting temperature condition of the regions of its invasion.

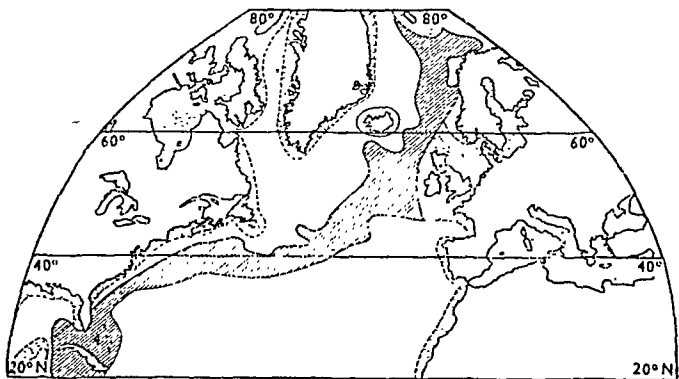


Fig. 95. Temperature excess of Gulf Stream drift at a depth of 600 feet (shaded area is 4° F warmer than average temperature of sea water in its latitude. Dots show continental shelf)—After Wust.

The velocity of the current is 10-15 miles per day in the open ocean. It is in contrast to 5½ m.p.h., speed of Florida current. Separate records show different facts, e.g., near New York the velocity is 72 miles, whereas farther east it is only 30 miles per day. At 36°N, 73°W it is about 120 cm/sec., while at 38°N, 69°W it reaches 140 cm/sec. The velocity of the current diminishes with the depth.

Further north of Chesapeake Bay on 40th parallel where the Gulf Stream turns eastward, the cold Labrador current which joins it is responsible for diminishing its original character of high temperature and salinity. Up to 45° W, south of Grand Bank, the stability of the current is maintained between 50-75%. But after this, the force is lost and momentum is only afforded by the westerly wind.

The volume of water north of Chesapeake, calculated on the basis that no motion is found below 2000 m, is between 74 and 93 million

$\text{m}^3/\text{sec.}$, i.e., 26 mill. $\text{m}^3/\text{sec.}$ by Florida current + 12 mill. $\text{m}^3/\text{sec.}$ by Antilles + between 38 and 57 mill. $\text{m}^3/\text{sec.}$ of Sargasso. According to Soule, 40 million $\text{m}^3/\text{sec.}$ water is transported towards south up to 45°W off the Grand Banks tail. The actual observations show that inflow north of Antilles current is between 15-20 mill. $\text{m}^3/\text{sec.}$ and the southward flow is 15 mill. $\text{m}^3/\text{sec.}$ Rossby has given the name of "Wake Stream" to this current on the basis of its continuous increase of volume transported downstream by lateral mixing from the sides. He further states that such currents must have a compensating current on the right and a counter current on the left. Lateral mixing, due to transverse circulation of absorbing right hand water and discharging in the counter current on left, takes place resulting in eddy formation.

As regards the fluctuations in the current, Marmer states, "Gulf Stream must be subject of fluctuations as regards temperature, velocity and location. Flowing winds will not only accelerate or retard its velocity depending on the direction of these winds, but will also carry its waters into regions which at other times it does not invade." Another marked feature along the American coast is that the sea level increases from St. Augustine to Halifax. The value of slope according to Parr is 17×10^8 .

(c) *North Atlantic Current.* Eastward of the Grand Bank and of 45°W the Gulf Stream breaks into various branches, demonstrating itself only as a slow moving easterly current. This current is known as the North Atlantic drift, driven mostly by the westerly wind. Here the current, in spite of losing much of its character, is a warm, saline current, and is divided in two parts.

The northern branch flowing north-east of 45°N latitude is flanked by the Labrador current on the west. Hence due to mixture of cold water, the original nature of the current is slightly changed. However, after some distance this branch is further divided into sub-branches. Some part of the water flows in the Norwegian Sea along the coast of Norway across Wyville Thompson ridge. The other part flows north and north-west, as *Irminger current* south of Iceland. Again, a small part moves (as far as Cape Farewell where 35‰ salinity water is found) southward along the Greenland coast and mixes with the East Greenland current.

The other branch of this Drift, which is comparatively warmer due to lesser mixing of cold current, moves eastward in 45°N latitude. It flows along the coast of France, Spain, and Azores island. Some of its water enters the Mediterranean Sea. An important branch was noted by Rennell (in 1793) in the Bay of Biscay, known as the Rennell current. This current runs along the north coast of Spain and France. After that a part of the current moves in the English Channel, while the remaining moves south of Ireland and joins the main Gulf drift. During winter this easterly current is more marked on the north coast of Spain. The velocity in January and July is 12.7 sea miles and 14.1 sea miles per day respectively.

Still another branch of the southerly drift flows along western Spain across Azores up to the coast of Africa. It changes in nature due

to upwelling of cold water along the coast. Hence further it is known as *Canaries cold current*.

The temperature throughout the drift is generally uniform, that is, 16°C at the surface which lowers down at the bottom. In June, 1939, a German 'Altair' Expedition noted great variations in temperature (between 7° — 13° at 600 m and 5° variations within 40 miles) either due to the bottom topography or by turbulent mixing due to travelling.

According to Helland-Hansen and Nansen, there is no clear current in this part but diffuse transport of water takes place towards the south.

Canaries Current. The current flowing along the western coasts of North Africa between Madeira and Cape Verde is known as the *Canaries current*. The Gulf drift water flowing here almost loses its original character and is transformed into a cold current. The velocity of the current varies from 8 to 30 miles per day. It carries water from the high latitudes to the equatorial region, and finally merges into the north equatorial current. Only a minor portion enters the *Guinea current* flowing just southward along the African coast.

The periodic variations are also marked in the current. Its southern boundary is shifted farther south in March and towards north in September. The cold water boundary shifts farther north of Gibraltar in summers and shifts to south during winters. Off the mouth of Gambia River the recorded sea temperature is 18.3°C .

The origin of the current is attributed to the trade winds which drive away warm waters far off the coasts, hence cold water upwells along the region. The Gulf drift moving south to some extent also helps in the maintenance of the current. Again, as a result of diversion of the North Equatorial waters from the African coast, this current flows to South to compensate for the loss.

Labrador current. Another circulation that comes in view in the North Atlantic is from the Baffin Bay and Davis Strait. It brings about 7.5 mill. m^3/sec . of water but receives little contribution from the cold water that flows down along the east coast of Greenland. Under the stress of the prevailing east, south-east wind the water of low salinity and temperature flows from the sub-polar area along the east coast of America which is also supplanted by other tributary currents coming through the islands. The free communication of water between the Labrador Sea and the Atlantic makes it possible for the Labrador current to flow with a continuous southerly flow. Above the depth of 1500 m. it carries 5.6 million m^3/sec . of water along the Labrador coast. Further, Smith recorded that 1.9 mill m^3/sec . of Labrador water sinks below the surface and moves as deep water in the Atlantic.

The velocity of the current in the Baffin Bay and Davis Strait is $6\frac{1}{2}$ sea miles per day. At 53°N off the Labrador coast, it is measured to be 11.8 sea miles per day.

Further south, the current strikes the coast of Newfoundland, then flows over the easterly part of the Grand Bank and merges with the Gulf

Stream east of 50° W. According to some authors a branch of this cold current moves west of Newfoundland along the coast of Nova Scotia and New England, as far as Chesapeake Bay in the south. But one of the recent observations shows that this idea is not true. E. H. Smith (1900-1930) during an expedition in Davis Strait and Baffin Bay studied the nature of the drift track of icebergs. The movement of icebergs proved that the current moves along the south tail of Grand Bank and not along south-east coast of U. S. A. as previously thought. Schott and Johnstone also agree that as a stream Labrador water never gets west of Grand Bank.¹

On the west from Halifax to Cape Cod the difference between the Labrador and the Gulf Stream is marked by a 'cold wall'. According to some the cold water flowing along the U.S. coast is said to be the result of cold water from the Gulf of St. Lawrence flowing as the "Cabot current".

However, the Labrador current does not vanish after being mixed up with the Gulf Stream because of higher salinity and density that it attains by mixture. It sinks down as sub-surface current below the main Gulf Stream in the middle latitudes. It is observed between 35°-36° N and 55°-45° W that a deep cool water layer exists near the bottom.

One of the important characteristics of the Labrador current is that it brings down icebergs along with it from the Baffin Bay. Near the vicinity of Newfoundland and Grand Bank, various icebergs are noted causing hindrances in navigation. The extent to which icebergs are found depends on the season, volume, velocity, and temperature of the Gulf Stream. Sometimes icebergs along with the easterly flow of Labrador over the Flemish ridge (east of Grand Bank) drift into the Irish current.

Sargasso Sea. The current map of the Atlantic (Fig. 91) would show an anti-cyclonic circulation of currents in the North Atlantic Ocean formed by the Gulf Stream, the Canaries current, and the Equatorial current. In between this gyral there is a calm and motionless sea, named the Sargasso Sea.

The name of the sea is derived from the Portuguese word 'Sargassum' meaning sea weed. It is a fact that the sea is covered by sea weeds, extending for miles and miles and thus hindering navigation. The origin of the Sargasso Sea in the midst of the Atlantic Ocean can be attributed to the existence of the circulatory currents on all sides which make this part of the sea completely motionless. It may also be noticed that this region is situated at the transition zone of the westerlies and the trade winds. Therefore, due to anticyclonic conditions light winds prevail and the central water is prevented from being mixed with the open ocean water.

Similar seas are not found in the South Atlantic or in the Pacific. The motionless area is found due to the particular shape of the central Atlantic, that is, being particularly narrower than the other oceans in similar latitudes, and due to the force of the North Equatorial current and Gulf Stream. These two currents move with a speed around the

¹ Church P. E., "Labrador Current", *Geographical Review*, Vol. 34, p. 375.

Sargasso Sea and hence prevent the mixing of water inside. In other oceans the currents are not so strong and the gyral is not complete; therefore, mixing from open ocean is not prevented.

The extent of the Sargasso Sea can either be delimited on the basis of the possibility of occurrence of weeds or on its actual occurrence. The latter is no doubt considered to be a better method of the judgment. The area of the sea, as stated by Marmer, is found between 20° and 40° N and 35° and 75° W longitude with an oval shape—the hump extending northward of Bermuda. Winge, after an observation, gives slightly different boundary of the Sargasso Sea. On the east 27° W longitude forms the boundary and in the south it corresponds with the 30th N parallel. But towards the east the extent of the boundary line is just south of 20° N latitude. In the north, the 40th N parallel forms the boundary. It swings towards south-west up to the latitude 35° N and again turns sharply upward to 45° N latitude (due to the force of the Gulf Stream). On the west, the boundary follows the coast of North America as far as 40° N. South of it, the boundary is not drawn due to lack of information.

The Sargasso Sea is known for its high salinity amounting to 37.0% . The whole Atlantic possesses an average salinity of 35.50% , whereas in between $20-40^{\circ}$ N it is 36.60% . The higher salinity in the Sargasso Sea, in comparison with the surrounding area, is due to high temperature and greater evaporation. Side by side, the lack of mixture of fresh water either as a river water or rain water from the coast or ice water, has also preserved this nature of the Sargasso Sea.

The temperature in this part of the Atlantic is also higher being situated in the lower latitudes. The average yearly temperature is about 26° C. There is an excess of evaporation due to cloudless days.

The sea weed or 'Sargassum' is found in abundance in this sea. It presents a great problem regarding its actual extent and origin. The thick malted weed, according to Humboldt, is found between the two banks: one is between Flora and Carvo from 40° W to 20° N, and the second bank at 70° W. The weeds occur in scattered masses of 100 feet diameter, though one square acre patches are also noticeable. The central part of the weeds is found to be thickest. According to Dixon, the floating weeds of Sargasso amount to about 20 million tons. Germain records that the weed is spread in 2 million square miles of the area but other sources mention about 11,000 sq. kilometer extent. Sometimes due to wind, the long strips of weeds have been noticed stretching in the wind direction. Captain C.C. Dixon has written about this feature in the Sargasso, "the winding bands of water free from weed look exactly like a river. The length and the direction of these slightly winding 'rivers' appears quite fixed..... But they are in truth phantom rivers".¹

Various ideas have been put forth to explain the origin of the weeds. The earliest theory was based on the assumption of banks near Azores and Bahamas on which Sargassum grows which after being plucked by waves and winds was brought by currents in the Sargasso.

¹ *Geographical Journal*, Nov. 1925, p. 43.

Another theory supported by Krummel, propagates the idea of gulf weed carried by Gulf Stream into Sargasso Sea from the shores of West Indies and Bahamas. But neither such weeds are found on the banks of West Indies and Bahamas nor their roots are attached to the bottom.

The third and the latest idea states that the gulf weed is a different type of species which grows only in the open seas. It is a floating plant without any root. According to D. O. Winge (1923), "this drifting weed does not come from the coast but lives and propagates by partition in Sargasso Sea. Drifting Sargasso weed is destitute of the ordinary organs of reproduction, which are found attached to coastal forms. Further, such species are not found growing attached anywhere along the coast. The absence of root thus favours the independent origin."¹ Winge finds three species of *Sargassum*.

Germain² states that the Sargasso weed is a type of littoral flora which is suddenly isolated from the coast and has adapted itself in the new environment. Regarding its origin, Germain agrees with the hypothesis of foundering of the continent in Miocene period just in the midst of the Atlantic at the present site of Sargasso Sea. The present floating sea weeds were formerly fixed to the shores of the foundered continent which adapted themselves to the regime of the open ocean. Thus there is an absence of an intermediate species between Sargasso weeds and the American coast weeds. This fact proves the sudden adaptation of the weed to the environment.

Germain has also given interesting observations regarding the occurrence of fish in this sea. European eels have breeding grounds in the warm and saline waters of the Sargasso. After spending about five or seven years in the western Europe and in the Mediterranean they come to spawn and die. Sea birds are absent as their prey find suitable hiding places in the weeds.

SEAS ADJACENT TO NORTH ATLANTIC

Currents of Caribbean Sea and Gulf of Mexico. Highly saline water of 36.5‰ salinity and high temperature (81°F) enters the Caribbean Sea from the equatorial region. There are two observed movements. The main movement of the water is due to the stress of the trade winds from east to west and piling action found at the Yucatan Strait. It is only in the southern part of the sea that the main current is seen following the coast of S. America and Yucatan as shown in Fig. 96. It is actually formed by a part of the North Equatorial current. The combined water of the North and South Equatorial currents is known as the Caribbean current in which the water is flowing with a speed of about 30 miles per day. After crossing the Yucatan channel this current is known as the Florida current which sweeps across the northern coast of Cuba through the Florida strait with somewhat similar speed. On the northern coast of West Indies another current diverted from the Equatorial current flows northward. This is called the Antilles current and carries

¹ Winge, D.O., 'The Sargasso Sea—Its boundaries and Vegetation', *Geographical Review*, Vol. 15, p. 149.

² Germain, Louis, *Geographical Review*, Vol. 26.

about 12 mill. m^3/sec of highly saline water mixed with the Sargasso Sea water. Iselin remarks that the current continuously increases in volume by absorption of Sargasso water.

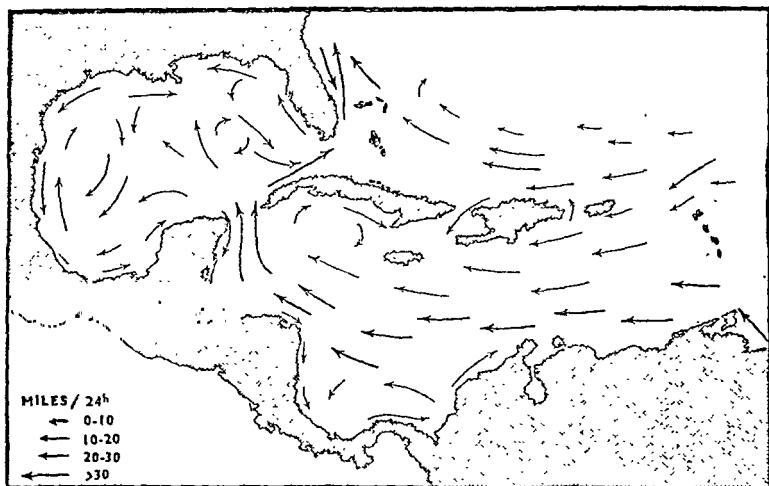


Fig. 96. Surface currents in spring in the Caribbean Sea and the Gulf of Mexico (After Dietrich).

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Apart from the main current, many eddies and swirls are also found between the Nicaragua and Columbia coast, Cuba and Jamaica, and in the Gulf of Mexico, which are mainly governed by the submarine and coastal topography. Actual observations reveal that in the Gulf of Mexico, west of the Mississippi delta, the current runs in opposite direction, due to the deltaic water deflected by the rotation of the earth.

Mediterranean Sea. The Mediterranean Sea is a comparatively enclosed sea of high temperature and high salinity which communicates with the Atlantic Ocean only through the narrow strait of Gibraltar. Due to the excess of evaporation over precipitation and run off in this region, the water of high salinity and density is formed at the surface which sinks to the bottom. The surface salinity is usually 37.00% and except for the north of Africa, temperature increases from the strait of Gibraltar to the inner areas. At the surface, the flow of water is found from the Atlantic through the strait which moves towards east along the African coast as shown in Fig. 97. According to Schott (1915) the total inflow of Atlantic water in the Mediterranean amounts to 1.75 mill. m^3/sec . The temperature of this current is 13°C and salinity is 36.00% . The speed of the current in some areas is 200 cm/sec . and close to the African coast it is 2 knots or 100 cm/sec . The surface current further flows along the coast of Turkey, Greece and Italy, south of which it turns again towards the African coast. This current is joined by the Black Sea current which is a light surface water of low density and flows

through the straits of Bosphorus and Dardanelles. The current here is 4 km. wide with a depth of 40 to 90 m. A. Merz has calculated the inflow in the Mediterranean and the outflow to the Black Sea as 12,600 m³/sec. and 6100 m³/sec. respectively and the salinity values change for the same from 38.50 to 35.00‰ in the Mediterranean and from 36 to 30‰ in the Black Sea.

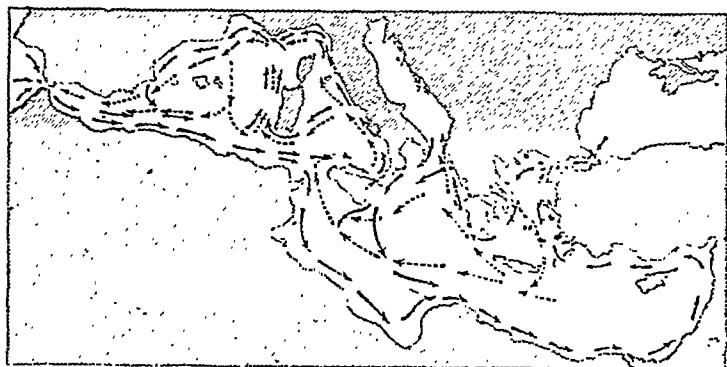


Fig. 97. Surface currents (solid arrows) and currents at intermediate depths (dashed arrows) in the Mediterranean Sea (After Nielson).

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Another circulation in the Mediterranean Sea moves west of Sicily, a bifurcation of the main current, and flows along west Italy and Spain, after which it again turns southward.

The thickness of the surface layer or the boundary surface separating the inflow and outflow in Mediterranean amounts to 100-200 m. and in the strait it is 125 m.

TABLE 1

Gains	m ³ /Sec.	Losses	m ³ /Sec.
Inflow from the Atlantic Ocean	1,750,000	Outflow to the Atlantic Ocean	1,680,000
Inflow from the Black Sea	12,600	Outflow to the Black Sea	6,100
Precipitation	31,600	Evaporation	115,400
Run-off	7,300		
	1,801,500		1,801,500

Apart from the surface flow, the dense water sinks at places and moves outward into the Atlantic through the strait as shown in Fig. 97 by dashed arrows. It has a salinity amounting to 38.40‰ and a

temperature 13°C . Due to intense mixing, the salinity is further reduced, but it remains higher than that of the Atlantic water in which it flows for a considerable distance.

Thus we see that there is a balance for the outflow and inflow of water in the Mediterranean. It is calculated in Table 1.¹

Norwegian Sea. The main North Atlantic Drift flowing west of England and Ireland is divided into many branches. Here the current is known as the Norwegian current. It flows across the Wyville-Thompson Ridge and enters the Norwegian Sea as shown in Fig. 98. The nature of the current is changed from the original though slight warmth remains in it. The inflow of the Atlantic water into the Norwegian Sea has a general salinity of 35.3% and a temperature varying between 4°C and 8°C . One of the branches moves towards the south of Greenland at 60th parallel. From Iceland it flows to the west and south-west as Irminger current with an average velocity of 2.4 miles per day. It runs up to Cape Farewell along east Greenland coast but soon loses its identity. Due to offshore wind from Greenland, the cold east Greenland current invades this warm current region and the cooling effect is felt to the depth between 125 and 250 m. The water is carried into the Davis strait though the current is changed in nature.

The other current of the Norwegian Sea flows along the coast of Norway and Sweden and thus enters the Arctic Ocean. The velocity of the Norwegian current as computed by the investigators is 30 cm/sec. Periodic variations are also noted in this current. Near about 63°N many branches are thrown off from this current. One branch turns westward and after crossing small distance it again moves to the south and thus forms a most complicated circulation of numerous eddies and whirls between Iceland, Scotland and Spitsbergen, as shown in Fig. 98. Just here another branch moves towards south of Svalbard Archipelago and again moves downward in the form of eddies. The major branch of the Norwegian current is found entering the Barents Sea.

Some of the left bank eddies of the main current sink beneath the cold water of the east Greenland current as a result of increase in its density by mixing of saline water. Thus a warm layer of 13°C at 550 fathoms depth is found in this ocean. On the western side of the current, numerous whirls are found which are related to the bottom topography. One of the small branches of this current enters the North Sea under the stress of stormy winds and records a counter clockwise circulation joined up in the north by the Baltic current flowing out through the north of Denmark. The Baltic current itself is mainly governed by local winds and hence exhibits numerous variations. North of Spitsbergen and east of Greenland the current is also influenced by the winds. Thus the Atlantic water submerges below the Arctic surface water and rests as a warm intermediate layer. Similarly in Barents Sea a counter clockwise circulation of warm water prevails on the eastern side and the cold Arctic on the western part of the sea. Variations are also recorded in the North Siberian shelf due to differences in the discharge of fresh water by Siberian rivers. Helland-Hansen points

¹ Sverdrup and others, *The Oceans*, p. 648.

out one of the major changes in the current during 1929 when it contained water of high temperature and salinity.

On the western part of the Norwegian Sea, a cold current flows from the Arctic Ocean along the east coast of Greenland owing to the prevailing northerly winds. Water here is colder and salinity is low since it contains much of the floating ice. Consequently, higher sea level is found on the eastern coast as a result of melting of ice and the presence of

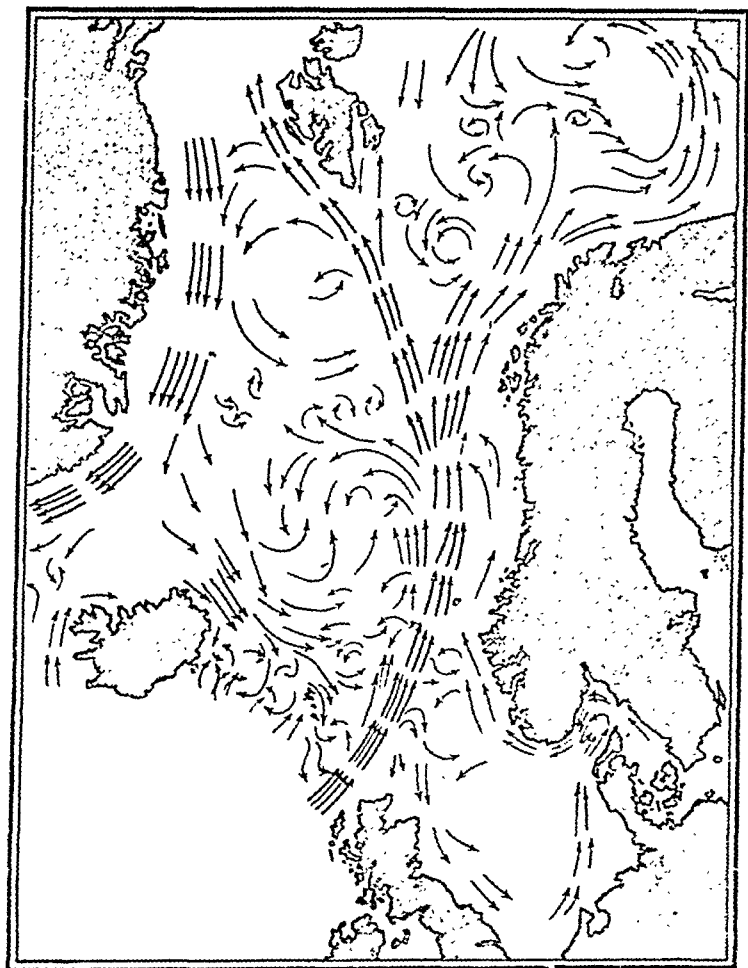


Fig. 98. Surface currents of the Norwegian Sea (After Helland-Hansen and Nansen)

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light water. The current flows along the continental shelf of the east coast and rounds along the Cape Farewell up to the western coast. The current is helped by wind and therefore the water is drifted further northward.

SOUTH ATLANTIC

In the South Atlantic also a complete gyral of currents is formed in an anti-clockwise manner. This central gyral is not so well marked as in the North Atlantic. The South Equatorial current, Brazil current, West Wind drift and Benguela current form this gyral. There is also no central region of similar nature as the Sargasso Sea.

Brazil current. The South Equatorial current flowing westward is prolonged along the South American coast. It moves southward as far as 40°S , and henceforth it bends round to the east as a result of being deflected to left hand side by earth's rotation. Brazil current is a comparatively feeble current and its average velocity ranges between 20 sea miles to 24 sea miles per day. It carries $10\text{m}^3/\text{sec.}$ of water from the equatorial current towards the south. It is a water mass of high temperature and high salinity which flows as far as the coastal banks of Patagonia. But observation reveals that the Brazil current disappears after 30 to 35°S as the cold Falkland current approaches northward along the south-east coast of Argentina. Similar to the Gulf Stream, the cold bank is visible in the southern hemisphere also which separates the cold coastal waters of Falkland current from that of the Brazil current, though it is not so well marked. The coastal water remains between 6° to 10°C temperature. The splitting of Brazil current is found in front of Laplata estuary. Most of the water here turns towards the east. But it soon loses its identity in the open ocean.

Falkland current. The Falkland current was first noted by Wilkes in 1839. Just similar to the Labrador current, the cold water of Antarctica moves on along the Argentina coast up to 30°S under the stress of westerly winds. The cold water is also upwelled due to eastward deflection of the warm surface water of Brazil current. The indication of northerly drift of the current is indicated by the distribution of icebergs brought by the current from the Antarctica region. The temperature records show 2°C at 274 m.

South Atlantic drift. Under the influence of strong westerlies the ocean water between 40° — 60°S moves from west to east. It is actually a continuation of the easterly deflected Brazil current and north-east Falkland current. According to Rennell, the current is common in all the southern oceans and runs in the direction of the earth's rotation from west to east. The South Atlantic current is shallower due to the presence of the Antarctic intermediate water. In the eastern part of the current, a branch of cold water is diverted along the coast of W. Africa. The velocity of the current is found between 6-33 miles per day. According to 'Challenger' the velocity near the Cape of Good Hope amounts to 15.8 sea miles per day.

Benguela current. The cold current flowing northward along the western coast of Africa is known as the Benguela current. There are

various approaches to explain its origin. Primarily, the deflection of the cold South Atlantic drift at the southern tip of Africa causes a northward movement along the coast. Secondly, the upwelling of the cold water from the bottom must be taking place and this process is further helped by drifting away of surface water from the coast under the stress of trade winds.

The upwelling creates areas of specially low salinity extending up to 200 km. from the coast. According to Deacon, the cold water off the south-west coast of Africa has upwelled from the Antarctic intermediate layer, originating 100-200 miles north of Antarctic convergence. The layer results due to the mixing of warm water flowing southward, with the sub-Antarctic surface water, to which Deacon gives the name of the Antarctic intermediate current. The current is particularly conspicuous between the Cape of Good Hope and 17°S and according to the rules of dynamics the denser water of low temperature flows on the right side, i.e. along the African coast, and lighter water on the left side. North of 20°S the current moves towards west and merges into the South Equatorial current. Along the African coast many eddies and whirls bifurcate from this cold current towards the Central Atlantic between 20° and 30°S.

North of the Table Bay up to Congo estuary, this cold current has an average velocity of 10 miles per day. But near the African shores the current is irregular and weak though exceptionally strong near Congo mouth. The temperature is lower near the coast and gradually increases in the open sea. But the temperate areas are marked along the coast due to upwelling.

Marchand considers the area of minimum temperature lying in Hondeklip Bay and Luderitz Bay. But African Pilot places the minimum temperature as far as the latitude 16°S. North of this latitude the temperature increases. At 15°S it is between 60°F and 67°F, whereas at 13°S it is about 75°F. At Water's Bay just within the tropics, the sea temperature is 5.7°C lower than at Durban (21.8°C).

Along the western coast of Africa there is a small counter current flowing towards the south. Therefore, in the south the inshore water is colder than the water few miles out into the sea.

Chapter 15 | CURRENTS OF PACIFIC OCEAN

The currents of the Pacific Ocean reveal the same pattern of movement of water masses as that of the Atlantic Ocean, i.e. the northern hemisphere is dominated by clockwise gyral and the southern hemisphere by anti-clockwise gyral. Among the currents the following are well developed.

CENTRAL PACIFIC

North equatorial current. (This current moves from Revilla Gigedo Island (Mexico) to the Philippines island covering a distance of 7560 sea miles. In the eastern part of the ocean, the current derives its waters from the Californian current and the south-east monsoon drift flowing north along the Mexican coast. From east to west the volume of the water increases continuously, as many eddies and small currents join this major current from the right.) In the eastern part between the Hawaiian and the American coast, much of the North Pacific water is added to this current. Before reaching its western boundary the north equatorial current branches off towards north and south. The northern branch bends through the Balintang channel into the China Sea, a part of which flows round the island of Formosa and joins the Kuroshio current. The southern branch turns abruptly and forms the Pacific counter current.

The north equatorial current is quite continuous in the Pacific Ocean, though minor seasonal variations are noted. The southern boundary of the current lies at 10° N in summer and at 5° N in winter. Near Marshall island, the southern boundary is placed just south of Kwajalein about 9° N and the northern boundary extends up to 30° N. Because of no obstruction in the open sea, the current is broad in the middle and is surrounded by many eddies.

The velocity of the current ranges between 12 and 18 sea miles per day, with a maximum velocity of 20 cm/sec. In a cross section, a spiral movement, with ascending motion is noticed at the southern boundary of this current and a descending motion at the tropical convergence near northern boundary. Thus in the current, surface water moves towards north and sub-surface water moves towards equator. This spiral movement becomes complicated due to greater distance found in between the divergence and the convergence, and also because of the presence of many local divergences and convergences.

During northern summers, the whole current is shifted towards the north, whereas in winters it moves towards south. But throughout the year, the current remains north of the equator.

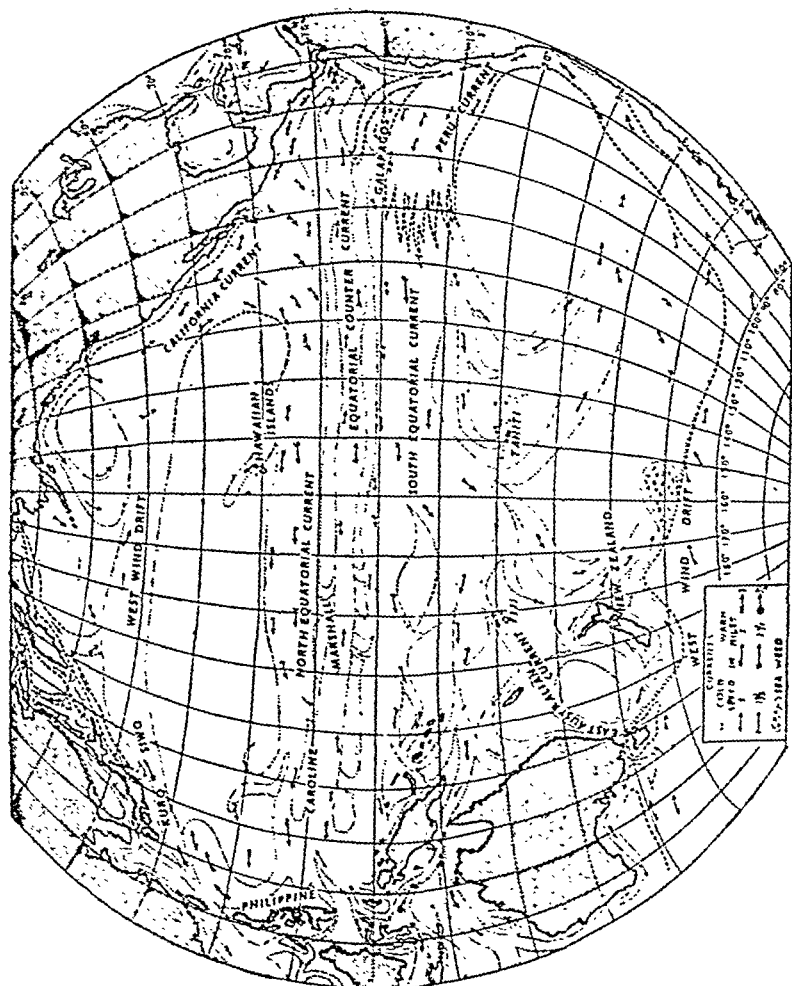


Fig 99. Surface currents of the Pacific Ocean.

South equatorial current. The origin of the South Equatorial current is also attributed to the action of the trade winds from east to west. The current extends for about 8500 miles. In the eastern part of the ocean, the cold Peruvian current moves northward and loses much of its character, being mixed with the warm equatorial waters. This current is recorded to be stronger than the North Equatorial current. The velocity here is 20 miles per day, whereas highest recorded velocity is 100 miles per day. Similar to the North Equatorial current, various eddies and small currents join this stream from the left. Further west, it is divided

into too many branches due to the rugged nature of the bottom and the surface topography. It is in this part that numerous submarine plateaus (volcanic etc.) are found which deflect the current. Similarly due to many islands in central and western region the southern part of the current is completely branched off. But in the northern part, the boundary lies near about 3° N. At the eastern end of the South Equatorial current one branch flows north of New Guinea and turns northward into the Equatorial Counter current. The other two distinguished branches move towards the northern and eastern coast of Australia as shown in Fig. 99.

Equatorial counter current. The dynamics of the counter current, whether in the Pacific or in the Atlantic or in the Indian Ocean is related to the distribution of mass development of surface gradients and the equatorial currents. North and south equatorial currents between 25° north and south latitudes is the zone of the north-easterly and south-easterly trade winds which drive forward the waters of the currents in the form of north and south equatorial currents towards the west. In between these two currents, a zone of calm belt is found where no stress is exerted on the oceanic surface. Hence the absence of any current in this portion is possible. However, after many observations by Montgomery and Palmen, it was concluded that there is a counter equatorial current flowing towards the east between the north and south equatorial currents. The current was first recognised during the 'Carnegie' expedition in the Pacific. ✓

The origin of the counter current is attributed to the piling up of light surface water against the western boundary of the ocean under the stress of trade winds. To counterbalance this difference in the gradient from east to west a compensation current moves towards the east. According to Montgomery: "The trade winds by continually exerting a westward stress on the sea surface produce a westward ascent along the equator...the equatorial counter currents are found in the doldrums and apparently result simply as a down slope flow in this zone where winds maintaining the slope are absent."¹

According to Palmen the slope of the surface at equator amounts to about 4.5×10^6 . The equatorial counter current is of a very shallow nature, being confined to the surface layer only. In the northern hemisphere, the lighter water lies on its right side and the denser water on the left side, and *vice versa* in the southern hemisphere.

Apart from the slope factor, the easterly movement of the counter current is also originated because of being embedded between those water masses which are moving in opposite direction. Hence it is subject to great retardation and friction due to the lateral mixing with the westward flowing equatorial currents. The lateral frictional stress is directed opposite to the horizontal stress exerted by the trade winds on the surface. Due to this factor the counter current flows to the east and according to Montgomery and Palmen, even maintained throughout. Thus, the equatorial counter current presents a dynamical important link in between the entire system of the ocean currents.

¹ Sverdrup, H. U., *Oceanography for Meteorologists*, p. 183.

According to Defant, the friction caused between equatorial currents is not due to lateral but vertical mixing, as shown in Fig. 100. He points out four circulation cells in a vertical equatorial cross section. At the equatorial or tropical convergence in the northern and southern hemispheres, the surface water sinks downward and moves as sub-surface current towards the equator where the water rises upwards and spreads towards the north and south up to 10° N and 5° S. In between these two cells there are other two cells: the counter current cells between 5° — 10° N and a part of west equatorial cell between 0° — 5° latitudes. Within the counter current, though the transportation of water is mainly towards the east, the sub-surface water rises at the northern boundary near 11° N and sinks at the southern boundary near 5° N.

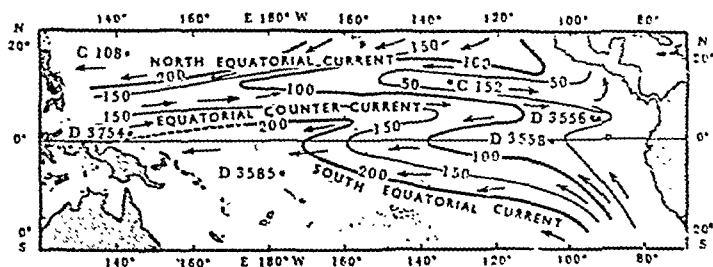


Fig. 100. Topography of the discontinuity surface in the equatorial region of the Pacific shown by depth contours in meters and corresponding currents.

(By permission from *Oceanography for Meteorologists*, by H. U. Sverdrup. Copyright 1945. George Allen and Unwin Ltd., London).

In the Pacific Ocean, the equatorial counter current is perhaps best developed. The south equatorial current is present on both sides of the equator up to 5° N while the north equatorial current is found north of 10° N. In between these two currents the counter current extends from 5° to 10° N.

The current runs in an easterly direction from Mindanao in the western part of the ocean to the coast of Gulf of Panama. In the eastern part it sends off branches in the Gulf of Panama towards the south. The lateral boundary of the equatorial counter current in the Pacific is not a straight line but a series of over-lapping waters of different masses. Near East Indies the boundaries and the character of the current change frequently due to stormy weather conditions. Puls, in 1895, published charts which showed the existence of counter current in all the seasons of the year but mostly in the northern hemisphere. During northern summers the counter current is farther away from the equator in the northern latitudes. In the Central American region variations do occur in the counter current and numerous eddies are formed along the coast which vary from year to year. It is only well developed in this part between 5° and 6° N. The greater part of the counter current along the American coast is diverted towards the north in the form of a strong current, and a weaker current turning towards south.

The uncertainty of the character of the current depends on the direction of the prevailing wind. In the Central Pacific the current is well established. As a result of observations near Marshall Islands, Barnes and Lyman state, "south of 7° north equatorial current it sets eastward. The velocity obtained from dynamic calculations was as high as 2 knots."¹ Local Marshall's navigators place the northern boundary of the counter current in this part, just south of Kwajalein about 9° N in the west and 10° N in the eastern part, whereas other investigators mark the northern boundary at 8° N. The southern boundary of the current is mostly vague though up to 4° N a strong easterly current is found. Again, a series of information of the natives of these islands show that the southern boundary near Gilbert island is at 2° N. The counter current according to them reveals two strong easterly flowing currents at 5° and 8° N with a calm strip in the middle.

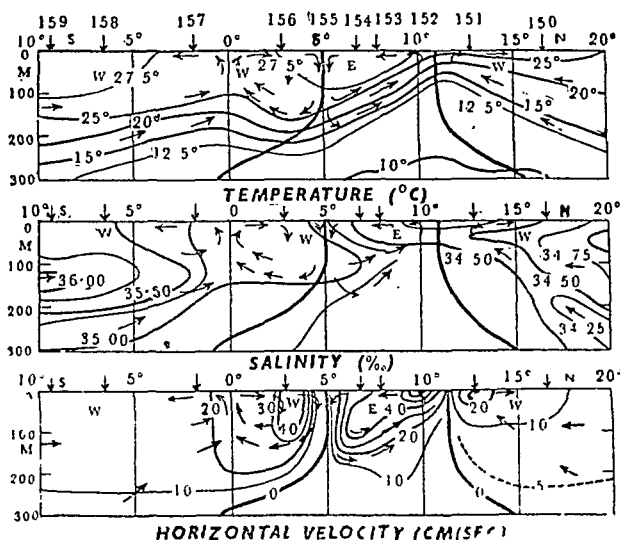


Fig. 101. Temperature, salinity and computed velocity in a vertical section between 10°S and 20°N in the Pacific Ocean. (Arrows indicate direction of north-south flow). E indicates flow to the east, W shows flow to the west). (After Carnegie observations).

(By permission from, *Oceanography for Meteorologists* by H. U. Sverdrup. Copyright 1945. George Allen and Unwin Ltd., London).

In the counter current near New Guinea and Philippines complications are found. According to Schott seasonal changes take place from June to August. The south equatorial current follows the north coast of New Guinea and converges sharply with the north equatorial current at about 5° N from where the counter current moves towards east. From December to February the north equatorial current bends along

¹ *Geographical Review*, Vol. 40, 1950.

Philippine islands. One of its branches goes off towards the north coast of New Guinea and the other branch, i.e. the counter current, moves towards the east. During northern summer, the velocity of the current reaches 100 cm/sec. at the surface. As shown in Fig. 101, the vertical cross section across this part shows that in the upper 200 m. depth a constant temperature of 27.5°C and salinity amounting to 34.50‰ is found. The velocity as computed by Carnegie is only 40 cm/sec., whereas the maximum reaches little over 50 cm/sec.

The counter current transports 25 million $\text{m}^3/\text{sec.}$ of water towards the east which is comparable to that of the Florida current. The transportation is less in the western part of the ocean but increases in the east.

NORTH PACIFIC

Kuroshio System. Wust (1936) has given the nomenclature of "Kuroshio system" to all the branches of the Kuroshio which flow in north-easterly direction carrying warm water of the Formosa up to 30°N . After this it bends to the east, following the Japan coast (hence also known as Japanese current) and flows as far as the coast of America. The system includes the following branches: (a) Kuroshio. The portion of the current running north-east from Formosa to Ryukyu and close to Japan coast up to 35°N ; (b) Kuroshio extension. The warm current extending eastward in two branches up to 160°E ; (c) North Pacific current. A further eastward continuation which throws branches to south, as far as 150°W ; (d) Tsushima current. Branches of the main current into the Japan Sea; and (e) Kuroshio counter current. The large eddy on the right hand side of the Kuroshio.

(a) *Kuroshio current.* As the north equatorial current infringes on the east Asian islands even before reaching the western boundary of the ocean, it is diverted and deflected to the right due to the rotation of the earth, and follows the coast lines of Philippine and China. Thus it forms the Kuroshio current. In this portion of the current near about Ryukyu islands greater similarity exists between this current and the Florida current. The movement of the flow through the Ryukyu ridge at 30°N is also conformable to that of the Florida Strait.

The energy of the current is derived from the trade winds which blow continuously towards the west and pile up waters along the western boundary of the oceans. According to Koenuma, the Japanese oceanographer, the Kuroshio current between Formosa and South Ryukyu is 700 m deep and its maximum velocity is 89 cm/sec. The transport of water through this portion amounts to about 20 million $\text{m}^3/\text{sec.}$, while the maximum reaches up to 23 million $\text{m}^3/\text{sec.}$ According to Koenuma, again, along the coast the intermediate water flows with greater speed. Hence the maximum velocity attained is about $160\text{--}180\text{ cm/sec.}$, but this condition extends up to 140 km from the coast. At depth, a reversal counter current flows with 10 cm/sec. speed. Between Ryukyu and the continental shelf, near about 33°N , a weak counter current moves towards the south, while another counter current is towards the right, which carries large amount of water in opposite direction.

In this portion of the Kuroshio current the temperature is equal to that of the Florida current (8°C), but the salinity amounts to 35.00‰ which is a little less than the 36.00‰ salinity of Florida current. There is a large annual variation of temperature in this current, being subject to cooling in winters by offshore winds. Annual range south of Shiono-misaki is 9°C at surface, and 4.5°C at 100 m. The maximum temperature is found in summers and minimum in winters.

(b) *Kuroshio extension*. After 35°N under the stress of westerly wind Kuroshio leaves the coast of Japan and divides into two branches. One branch follows its original course towards the east, up to 160°E , while the other moves as far as 42°N towards north-east where it bends towards east. The vertical section through the current shows that in longitude 153°E it is a narrow current which is broken into many branches, eddies and whirls between 155°E and 160°E . Much of the water here turns southward to form the counter current.

In the north, the Kuroshio extension (just like the Gulf Stream) is in contact with the Oyashio current. According to the Japanese oceanographer Uda, numerous eddies develop here and a thorough mixing takes place. By observations, it is found that north of 36° up to 41°N the waters of Kuroshio are mostly mixed with the waters of Oyashio. Thus the salinity is as low as 33.8‰ up to the depth of 300 m.

(c) *North Pacific current*. Further movement of the Kuroshio current towards the coast of North America is mainly impelled by the prevalent west winds. A greater part of the water of this current turns to the south before it actually reaches 150°W , and only a small portion flows between the American coast and south of Hawaiian islands.

Towards the east, further bifurcations of the Kuroshio current are found. A part of the water moves southward as cold California current whereas the northward current is known as Aleutian current. In the latter the water mass is somewhat different from the south and is formed due to mixture of warm and cold waters of Kuroshio and Oyashio. The temperature and salinity is also lowered due to excessive precipitation and inflow of cold Arctic water. This branch is further divided into two branches. One branch enters the Bering Sea flowing in the northern part of the Aleutian islands. Thus it encircles the whole of the Bering Sea in anti-clockwise direction. Another branch of the Aleutian current is bifurcated near the coast of America which moves into the Gulf of Alaska in the counter clockwise fashion. This current loses much of its character while moving north but it is still warmer than the waters of the Alaskan Gulf. Therefore a strong influence is exerted on the climate of nearby land.

The other branch of the North Pacific current turns southward along the Californian coast. It is Californian cold current.

(d) *Tsushima current*. Near about 30°N , the main Kuroshio current throws a branch into the Japan Sea, flowing northward along the west Japan coast. It is known as Tsushima current. As the salinity and temperature of the water is high, it influences the climate of the coast, specially during winters,

(c) *Kuroshio counter current*. There is a big gyral in the centre of the Pacific Ocean east of Hawaiian islands in which water flows opposite to the Kuroshio. The location of the gyral changes according to the seasonal shifts; sometimes it covers the Hawaiian islands, and at other times it lies entirely to the north-east.

Oyashio current. Bering Sea is the only communication through which Arctic water enters into the Pacific along the eastern coast of Kamchatka. South of 50°N some of the cold water of this current moves towards east and mixes up with the Aleutian and Kuroshio currents. The current flows southward along the east coast of Japan in order to make up for the absence of water created by the diversion of Kuroshio to east under the stress of westerlies. The current is similar to Labrador current in most of its characteristics.

Californian current. Similar to its counterpart, the Canaries current of the Atlantic Ocean, the Californian current flows along the coast of America, between 48° and 23°N . It is supposed to be the southern continuation of the North Pacific current. The Californian current is a cold current which also exhibits a great amount of upwelled water along the coast. Under the stress of trade winds, the water along the American coast is thrown far away from the land and the cold sub-Arctic water takes its place by upwelling. This upwelling according to Sverdrup, Fleming and McEwen is from 200 m. with the rate of 20 m. a month. Thus there is only an overturning of the upper layers.

During the season of upwelling between March and July a counter current containing equatorial waters flows near to the coast at the depth below 200 m. This counter current is similar to the counter current of Peruvian coast. The nature of the former varies due to changing winds along the coast, while the latter has regular flow due to stable winds throughout the year. According to Johnson, towards the end of the summer the upwelling gradually ceases and the pattern of current is disturbed. Thus, numerous eddies develop in the region and a counter current is found flowing northward up to 48°N .

The western limit of the Californian current is made by the line which separates sub-Arctic water on the east and the North Pacific water in the west. The total volume of water that is transported by this current is measured to be 10 million m^3/sec . The velocity of the current is not great. Lowest temperatures in the current are found near the coast in three regions of upwelling, e.g. at 24°N , 35°N and 41°N .

In the south, when the Californian current enters the region of trade wind, it is deflected to the right and joins equatorial current.

SOUTH PACIFIC

Peru current. Peru current is perhaps the best studied current of the Pacific Ocean. According to Gunther, the name Peru current is applied to the whole of the current system along the South American coast. The part which is close to the coast is known as Peru coastal

current, as differentiated from Peru oceanic current. Sufficient knowledge of this current was gained in 1522. In 1553 Cieza de Leon gave further details of this current. The low temperature of the coastal current and an indirect reference to the warm counter current was made by Acosta in 1608. But it was Humboldt in 1802 who noted the details of the current and pointed out that the mean temperature of the South American coast is about 18° — 20° F lower than the temperature of the latitude. Thus, this current is also known as 'Humboldt current'. But later on, Gunther accepted the views of Hoffman, Krummel and Schott but he did not accept the name as 'Humboldt current'. In his opinion a regional name, i.e. the Peru current, would suit it well for Peru current includes two different types of currents: the cold and the warm currents.

The coastal water shows traces of upwelling due to which the nutrient salts are abundant and velocity is high, whereas in the open ocean the current is due to the movement of the cold Antarctica water towards north with no upwelling and hence a low velocity is observed. The transport of water is accounted to be between 10 and 15 million m^3/sec . The Peru current is quite wide and near 35°S its extent is 900 km from the coast. Schott places the northern limit of this current just south of Equator where the current moves to the west and mixes with the equatorial current.

The best surveyed portion in this current is that of the Peru coastal current where most of the upwelling takes place. Upwelling in this area was first noted by De Tesson. It is the result of the south-east trade winds along the coast of Chile and Peru which deflects the water away into the open ocean. Apart from the offshore wind this upwelling is also attributed to the sectional effect of winds and drift out at sea and the deflecting force of the earth's rotation. By the measurement of salinity it is noted that the source of upwelled water lies at depth between 100 and 360 m. Below this level a southward flowing water was found composed of sub-tropical and sub-Antarctica water. Still lower at 700 m is the Antarctica intermediate water which does not upwell at the surface. The origin of the current is attributed to the northerly deflection of the sub-Antarctica water moving in 40°S .

This current, as William Scoresby observed, is a single-handed divergence line along which waters from the depths are being mixed, then drawn off the coast, and again replaced by fresh waters. William Scoresby shows that the upwelling in this portion is also not a regular process. However, according to Schott and Gunther active upwelling takes place at four regions between 3°S — 33°S . Gunther mentions upwelling at 5°S and 15°S during winters when two tongues of warm waters flow along the coast and encircle the cold upwelled water. But Schott points out that these tongues of water do not vary year to year. In April to June, the whirls and eddies on the coastal side of the current bring high temperature towards the coast in between 9° to 12°S . This is distinguished as counter current or 'El Nino'.

The temperature observations in November along the coastal waters, as noted by Humboldt, were 59.9°F at Callao, considerably lower than the nearby tropical temperature. Significant observations of McEwen

regarding the temperature of the coastal waters reveal that there is a relatively low temperature in the close proximity of the land, whereas off shore along the lines perpendicular to the coast the temperature increases. This fact is due to the upwelling of the water along the coast as shown in Fig. 102. Another important fact is the extraordinary uniform temperature in whole of the current from north to south with little effect of the latitude. Coker mentions that uniformity extends as far as Valparaiso (Chile) in the south though it is specially formed between Molina and Paita (about 1000 nautical miles distance). Only small variations in temperature here are noted due to local changes. The average temperature of the water is between 58° — 64° F throughout the year.

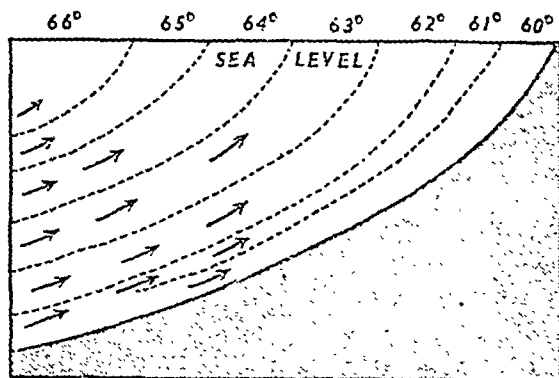


Fig. 102. Probable relation between the upwelling of bottom water and decreasing shoreward temperatures in the Humboldt current. (Width of cross section approximately 10 sea miles).

(By permission from *The Geographical Review*, New York, Vol. 13, 1923, p. 67).

The width of the current as mentioned by Stiglich is about 150 miles, but the readings of Hoffman show a quite narrow belt of cold water. The velocity of the current as computed by navigators is 15 miles per day or sometimes one mile per hour throughout the year. Observations by others show the average velocity of 0.91 statute miles per hour.

El Nino or Counter current. Close to the Peruvian coast, a subsurface warm counter current of Pacific equatorial waters flows southward at 400 m. at a distance of 180 km. from the coast between 3° and 36° S. North of 25° S due to excessive evaporation, the sub-surface water has lower salinity than the surface water, whereas south of this latitude it has comparatively higher salinity.

The current at the surface was observed by Coker who remarked that waters along the Peruvian coast show two different types of water masses, one warm and the other cold. The boundary between them is formed at the bend of the Peruvian coast. To the south is the upwelling of cold water, to the north is the water of stable equilibrium. Hence

the occurrence of a warm current was all the more proved. The existence of the current according to some is attributed to seasonal or occasional phenomenon under major disturbances or equatorial pressure changes, due to which its greatest southerly extension is found.

During summers, the Peru coastal current is extended northwards and converges with the equatorial counter current whose water mostly turns towards the north. But during winters due to the north-east trade winds the equatorial counter current moves towards south across the equator. Thus a reversal in the trend of the surface current is seen which drives the warm saline water along the South American coast. This fact was further confirmed by Gunther's observations which revealed the existence of a series of crests and troughs of the temperature along the coastal areas. Further, it was noted that at the convergence of this warm wedge, highly saline tropical water takes place permanently or seasonally at two points—Callao and Arica—while the northerly cold current is off the region of northern Peru and off San Juan region of southern Peru. The latter is associated with rich plankton due to upwelling of cold water, while the warm current on the coast was equally noted for the paucity of the plankton.

Rossby maintains that in the southern hemisphere waters flowing in the oceanic troposphere would give rise to counter current on its right side. Hence, along the Peruvian coast we find the counter current from the north-west along the coast and extending on the right side of the Peru current. According to Peruvian writers, the counter current proceeds from the river Guayas (emptying into the Gulf of Guayaquil) in the maximum outlet season, but the volume of water of El Nino is too much to account for this type of source.

The temperature conditions of the ocean water of El Nino in the month of January show a gradual decrease to the south from 70·2° F half a mile east of Lobos de Tierra to 66·5° F near the end of the Pier at Eten. The high temperature is an annual occurrence in the month of December in about 9° to 12° S north of Callao. At this time, 60·4° F temperature was recorded as usual off Pacasamy, and was raised to 69° F after two weeks due to the influx of the warm current. When the current reaches the latitudes of Talara 5° S in January the temperature is raised up to 77°—78° F. In March it becomes 80° F at Callao and 79° near Mollendo. But in the middle of April the normal conditions return. Captain G. S. Dexter recorded 68° F temperature at Callao and 60° at Pisco at the end of April. The surface salinity of El Nino is between 33·00‰ to 34·00‰. The strength of the current varies between $\frac{1}{2}$ and 2 knots. The velocity recorded near Callao in March varied from 1 to 1½ knots against the prevailing winds.

The effect of El Nino is seen in the warming up of the coastal waters, and bringing ample rains along the shores as a result of rising of the temperature of the ocean water. Allen has suggested that the drawing away of the cold upwelled water from the Peruvian coast and the flowing of El Nino to the south along the coast, account for the disappearance of Plankton and fisheries and the appearance of diseases of guano and pests. Unusual rainfall was recorded bringing flood and destruction to the land near about.¹

¹ *Geographical Review*, Vol. 13, 1933, p. 64.

East Australian Current. West of the south equatorial current, among many southward diverging branches, East Australian current is quite prominent. It flows through the Australian coast and surrounds the New Zealand island. It carries a considerable amount of warmth and salinity along with it. In spite of the varying winds during summer and winter, that is north-east in summer season and south-west in winter, the movement of the water is quite constant. At 40° S the water bends towards east under the influence of the rotation of the earth and the westerlies.

West wind drift. Similar to the Atlantic Ocean, there is also an easterly moving west wind drift in the Pacific which extends from Tasmania to the South American coast. Here the current is much more prominent due to the greater expanse of the ocean. The speed of the current is greater under the influence of 'Roaring Forties'. In the western part, the drift is joined by the warm waters of the East Australian current which is deflected towards the east. In South Pacific, at 45° S the current splits up into two branches: one branch flows south round Cape Horn into the Atlantic Ocean, and the other moves northward along the Peruvian coast due to the deflection of the current.

INDIAN OCEAN

The Indian Ocean differs from the Atlantic and the Pacific oceans in its characteristic current circulation. Consequently, it differs from the theoretical scheme of the circulation visualized so far. Being blocked in the north by the Indian, the African and the Australian continental masses, it actually represents only the southern part of the ocean. Hence, the general pattern of circulation corresponds to the pattern of the southern hemisphere, whereas the northern half, quite contrary to other oceanic bodies, develops a system varying according to the seasonal rhythm of the monsoons.

Currents of Northern Indian Ocean. North of the Equator, the waters of the Indian Ocean are completely influenced by the changing rhythm of monsoon wind system. Hence no particular current is found throughout the year, and changes are frequent in the form of a complete reversal of currents in winters and summers.

During the months of north-east monsoon, i.e. northerly winters, the wind friction drives the surface waters towards the western coast of Africa. At this time, the north equatorial current is best developed between Andaman and the Somali coast of Africa south of Ceylon in 5° N. At the same time, in the Bay of Bengal and the Arabian Sea also, the currents move according to the prevailing wind, that is, in the south-west direction flowing along the projecting land of the sub-continent. This current is known as N.E. Monsoon drift. But apart from the above, many complicated and large eddy systems are also established in this part of the ocean, specially in the Bay of Bengal and the Arabian Sea, as shown in Fig. 103.

Just south of this current a counter current is also marked whose main axis lies approximately in 7° S which extends from 2° – 8° S. This current flows towards the east, starting from Zanzibar to Sumatra with a velocity between 1 to 2 knots. It is also a well developed current in this season and gets its water from the N. E. Monsoon drift which joins the equatorial counter current by turning southwards.

In the months of August and September there is a complete reversal of northern circulation due to the predominance of the S.W. Monsoon. The two most important changes are the disappearance of the north equatorial current, which is replaced by the S.W. Monsoon current flowing west to east, and throwing branches into the Bay of

Bengal and the Arabian Sea, and the absence of the counter current. The latter is visible only in the form of many eddies moving in the easterly direction. On the eastern coast of Africa along Somaliland, a considerable upwelling takes place between 0° — 10° S as a result of west wind drift which, after crossing the Equator, strengthens the monsoon current further north. it is named as Somali current.

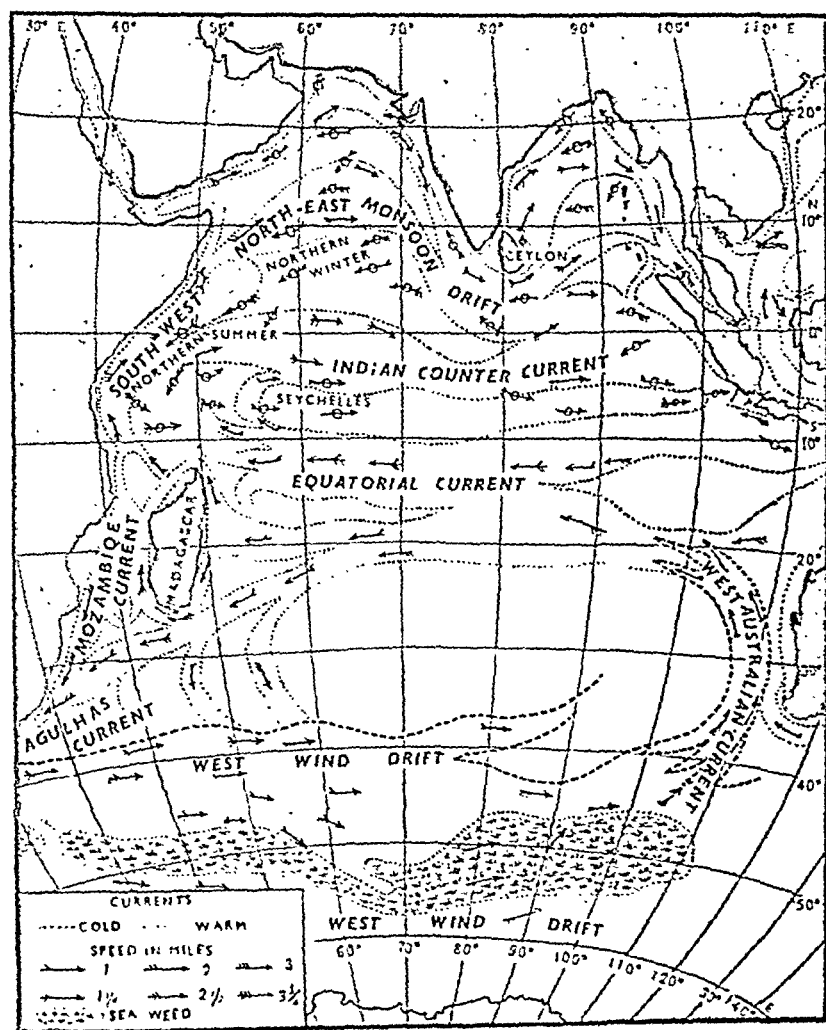


Fig. 103. Surface currents of the Indian Ocean.

Though the general movement of the water in the northern section of the Indian Ocean is towards the east in this season, yet a complete gyral can be detected. During summers a cyclonic gyral moves in the form of a westward drift of the water south of the Equator, which crosses the equator, runs along the African coast and turns eastwards as the S.E. Monsoon drifts. Further eastward one branch of the current turns southward along Sumatra island and mixes with the westward moving equatorial current, whereas another branch turns northward in the Bay of Bengal.

In the central part of the gyral, no current is visible but only eddies and irregular motion of the water are seen.

The anti-cyclonic gyral in the north Indian Ocean during winters is not much developed, yet a distinct westerly movement of the N.E. Monsoon drift carries water along the African coast which is drifted to the east in the form of the counter current. In the eastern part near the East Indies and the Australian coast the currents are very complex.

South equatorial current. Southern Indian Ocean is perhaps less marked by the seasonal changes, hence a south equatorial current flows north of 20° S between the Australian and the African coast. The main axis of the current is found between 10° and 15° S, with a well established flow east of 100° longitude where waters of West Australian current have joined it. The current strikes the coast of Africa near Madagascar and splits at 10° S into many branches, the major one turning southward to form the *Agulhas current*. But actual bifurcation of the current starts at 65° E where one branch moves towards the north and the other towards the south.

The seasonableness of the trades also affects the velocity of the current. During summer months, when south-east trade winds become powerful due to the impact of low pressure areas in southern Asia, the flow of the current is quite fast and strong, whereas in winters the speed and the location is hampered. In summers, the waters from the South Pacific and the West Australian current also give it a great momentum. In both the seasons of the year a part of south equatorial water turns north of Equator along Africa and to the south in the Mozambique channel.

Mozambique and Agulhas current. About 11° S a branch of south equatorial current flows southward along the African coast and joins the other branch of the same current which flows through the Mozambique channel. The current is known as Mozambique current up to 30° S after which due to confluence of two branches of south equatorial current it is known as the Agulhas current. According to W. E. Isaac, there seems no difference between these two currents as they form one complete stream of warm water flowing southwards from the tropics. Hence he suggests that it would be more logical to name the current 'Mozambique current'.¹

¹ Isaac, W. E., "South African Coastal Waters in Relation to Ocean Currents", *Geographical Review*, Vol. 27, 1937.

In the northern part, the Mozambique current between Africa and Mozambique is in the form of eddies and gyral but a well established stream develops after 25° S. Agulhas current is a narrow current and extends for 50 miles from the coast. The northern limit of this current is supposed to run parallel to Natal. However, the current attains the velocity of 5 knots at times, and ships have been carried by it against a gale at the rate of 3 to 4 knots. The Agulhas current follows the African coast up to the end of the continent as it is commonly believed. But according to Findlay, the current is actually carried beyond Cape Agulhas though the checking effect of the bank, south of the African coast, results in a gradual deflection to south-east. Deacon points out that the greater part of the sub-tropical water appears to turn back near the edge of the Agulhas Bank in about 22° E but sometimes the current has been found to penetrate westward of 10° E. To the south of Africa, greater volume of the waters of the Agulhas stream bends sharply to the south and then towards the east. Some of the water of this current also rounds up the Cape of Good Hope into the Benguela current along the west coast of Africa. In between the Agulhas current and the African coast, the upwelling and the occurrence of cold water moving northwards in counter direction is seen. This lowers the temperature of the coast, as may be noted in the decreasing gradient of mean annual surface sea temperature from Durban to False Bay.

West wind drift. Again, as found in the Pacific and the Atlantic, under the stress of westerly winds of southern oceans known as 'Roaring forties', the cold water in 40° S moves in the west wind drift with the easterly direction. After enjoying continuous flow towards the east, the current is bifurcated near about 110° E. One branch flows northward along Australia and forms the west Australian cold current. This current has temperature and salinity characteristics of Benguela and Humboldt current. At Tropic of Capricorn it bends towards west and north-west and near 100° E it joins the south equatorial current. The other branch of the main current moves south of Australian coast.

The west wind drift of the Indian Ocean is also subject to seasonal changes. During winters a greater part of the west wind drift passes south of Australia and minor branch turns along West Australia. But during summers, some of the branches turn northward before reaching Australian coast. Recent observations reveal that there is no sharp and well defined current on the west coast of Australia except a visible tendency of waters to move in the north during summers and winters.

In the South Indian Ocean also there is a visible anti-cyclonic gyral formed by south equatorial current, Agulhas current, west-wind drift, and west Australian current. In the central part of the circulation there is no permanent streaming and only eddies are found.

Due to scarcity of data, knowledge about the sub-surface currents and movement of Indian Ocean water is very scanty and doubtful. Due to the character of the water together with very low oxygen values of the northern part of the Indian Ocean, the Antarctic intermediate water probably flows northward but ends at a shorter distance from the Antarctic convergence. It is difficult to know the exact amount of water carried by the currents of the Indian Ocean.

ADJACENT SEAS OF THE INDIAN OCEAN

The Red Sea, an adjacent sea to the Indian Ocean, is important in the same manner as the Mediterranean is to the Atlantic Ocean. The geographical limit of the Red Sea is between 12° to 30° N. An open communication exists with the Mediterranean through the Suez Canal, and in the south with the Indian Ocean through the Gulf of Aden. At the strait of Bab el Mandeb, the maximum depth found is about 100 m.

Red Sea is located in a region of arid climate where greater evaporation and lesser run off is found. The climatic conditions and the prevailing winds are responsible for the exchange of waters between the Red Sea and the Indian Ocean. The salinity is usually between 40‰ to 41‰. The continental lowering of the temperature in winters lessens the sea temperature also. Hence, the formation of deep dense water takes place which flows out as sub-surface current. The study of Barlow (1934) revealed that surface current flows from Arabian Sea towards north or north-west into the Red Sea from November to March and to the south, south-east out of the Red Sea to the Arabian Sea from June to September. The transitional area is marked with the latitude of 20° N through which two water masses go. Due to the prevailing winds in northern part of the Red Sea the flow of the in-going water is made slower in comparison with the southern half.

The exchange of water between the Red Sea and the adjacent waters of Mediterranean Sea and Indian Ocean takes place through the Suez Canal and the strait of Bab el Mandeb respectively. The flow through Suez Canal is determined by three factors: (i) the difference in sea level between the Red Sea and the Mediterranean Sea, (ii) the prevailing local winds, and (iii) the salinity of canal water. The surface flow is from the Red Sea to the Mediterranean in all seasons except from July to September. The studies of Vercelli (1925) and Thompson (1939) account for the varying exchanges of waters between Red Sea and Gulf of Aden which depend upon seasonal changes in wind direction. In the winter season there is an incoming flow to the Red Sea and an outgoing sub-surface flow to the Gulf of Aden, whereas the reverse is the case in summers. The winter outflow of the Red Sea amounts to 0.48 million m^3/sec and inflow to 0.58 million m^3/sec .

POLAR WATERS

The Polar Seas are less known parts of the oceans due to their being mostly ice covered. Further, these parts are far away from the inhabited parts of the world and knowledge about them is gathered only at the expense of huge money and immense trouble.

Southern Ocean. The Antarctic currents are also not known in more details. The southern ocean is formed by the meeting of the three great oceans, namely, the Atlantic, the Pacific and the Indian. The Antarctic has two types of current, the relative currents according to the distribution of water mass and the wind drifts at the surface layers.

The character, flow and direction of the relative currents are determined on the basis of the distribution of the specific volume and its

anomalies in the water mass (specific volume is estimated in accordance with the density of the water). In general, the line of equal anomaly slopes from south to north due to density differences. In the southern hemisphere the denser water mass lies on the right side, so every current based on the specific volume should move from west to east. At the surface north of the Antarctic convergence a velocity of 15 cm/sec. is found whereas within the convergence it is 4.4 cm/sec. From the point of view of general movement of oceanic bodies, these relative currents are responsible for very insignificant amount of transfer of water.

The really important water movement is the drift circulation from west to east throughout the three southern oceans. It flows in an unobstructed manner excepting some deflections of the current on the left due to the continental masses. This west wind drift is present throughout the greater part of the year and because of the presence of the projecting continental masses it either bends towards the south or is deflected towards the north along the continents.

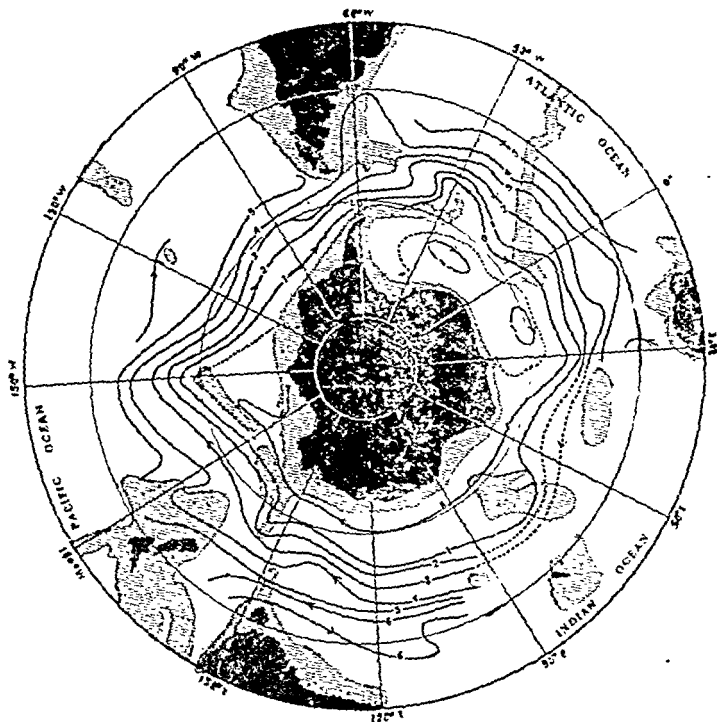


Fig. 101. Transport lines around the Antarctic continent. Between two lines the transport relative to the 3000 decibar surface is about 20 mill. m³/sec.

(By permission of the publisher, from H. U. Sverdrup, M. W. Johnson and R. H. Fleming, *The Oceans: Their Physics, Chemistry and General Biology*. (C) 1942, Prentice-Hall, Inc., U.S.A.)

Further, the circumpolar current close to the Antarctic convergence is distinguished from the rest of the west wind drift. Immediately adjacent to the continent of Antarctica, the flow of water is locally to the west, specially in the region of the Weddell Sea, as a result of the outflowing winds and their deflection to the left.

The transport lines and the direction of the flow is considered in relation to the main areas of divergence and convergence of the water masses. The sub-tropical Antarctic water results into the superimposition of transverse water movement over the general eastward flow. As regards the transport of the volume, Fig. 104 indicates that the transport between two lines equals to 20 mill. m^3/sec . This figure has been drawn on the data collected from Deacon's charts (1937) and by the addition of the result from a number of 'Meteor' stations in the South Atlantic. The transport line marked '0' in Fig. 104 is not continuous around the Antarctic continent. This indicates that some transport of water must take place across the lines. The area of a marked discrepancy between the lines of equal transport and the actual flow of water is the Drake Passage Region. The total transport of the Antarctic circumpolar current must be greater than what is shown in Fig. 104. This deduction is made on the basis that according to this figure the transport is 90 million m^3/sec , whereas later estimates by Clowes give 110 million m^3/sec .

The easterly and south-easterly winds blow near the continent and between 60°S to 40°S strong westerly winds prevail. So the westward currents near the continents and eastward general drift between 60°S and 40°S are found. In between these two systems divergence is observed. Further, the southward component of the Antarctic convergence and northward component of the subtropical convergence shows the dominance of thermohaline circulation over wind circulation. As previously stated, the result of these convergences and divergences is the superimposition of transverse circulation over the general eastward drift. This is, in general, the circulation pattern of the Antarctic Region but more complications will be found if more intensive study is made.

ARCTIC OCEAN

The Arctic Ocean is really an enclosed sea bounded by the great Eurasian and American land masses, allowing two outlets into the Pacific and the Atlantic oceans. The knowledge about the current system is the result of recent investigations and observations in the North Polar waters. The task of collection is very difficult because this polar sea, with other adjacent seas, i.e., the western portion of the Norwegian Sea, Baffin Bay and the western portion of the Labrador Sea, is covered with sea-ice during most of the year.

The general drift across the Arctic Ocean is from east to west; this was confirmed by the drift of the 'Fram' and water logged wood etc. The path of this current may be traced from the coasts of Siberia to the north-east coast of Greenland, passing further through the Hudson Strait into Baffin Bay. The main drift flows down the east coast of Greenland through Denmark Strait to Cape Farewell and enters the Davis Strait. Off shoots from this current are also traced into the North Sea.

In the Arctic Ocean, a great movement of water is noted due to the off shoots of the Atlantic currents coming from the south. The Gulf Stream, after reaching the northern coast of Norway, spreads out in a fanwise shape. It reaches up to 80° N. The second branch moves further north. At the islands of Spitzbergen, there are two types of flows: one on the western side of the island is an easterly flow and on the eastern side a westerly flow.

The Arctic cold water flows in the Pacific through the Bering Sea. But there is lesser possibility of mixture in Pacific water due to the shorter passage.

Chapter 17 | MAN AND OCEANS

Oceans form so great a part of man's environment that they have an overwhelming influence on man and his activities. The growing science of oceanography embraces all aspects pertaining to the sea and integrates the knowledge gained through the marine sciences. It indicates the dependence of man and his activities on the water bodies directly or indirectly.

The classical world did not emphasise the importance of oceans in man's life because they were not aware of their great magnitude over the earth's surface. After 1900 A. D. great advances have been made in all the marine sciences. The establishment of Research Institutions and the launching of expeditions by the various nations and, more recently, Geophysical researches in the polar waters have led us to realise the fundamental characteristic of oceans as a source of transportation and means of communication, as a source of food, and as a modifying factor in man's climatic environment.

Various government bodies and research institutions have studied the various aspects of oceans, viz., (i) effect on weather, (ii) effect on navigation, (iii) possibilities of developing planktonic food resources, (iv) development and conservation of world fisheries, (v) exploration of other new food supplies, (vi) experimentation with heat engines utilizing thermal differential between the top and bottom waters, (vii) geophysical research in the effects of volcanoes and earthquakes under the sea upon the safety of inland and coastal communities and beach control, etc.

Oceans and Climate. The principle of 'terrestrial unity' advocates the inter-dependence of various natural phenomena of this universe. There is a close inter-relationship of a complicated nature between the atmosphere and the oceans. The ocean is a great regulator and stabilizer of climatic elements and climatic changes. The distribution of temperature over the earth surface is greatly influenced by the oceans. They have been regarded as "a savings bank for solar energy, receiving deposits in seasons of excessive insolation and paying them back in seasons of want". The enormous absorbing and radiating capacities of the oceans do not allow much extremes of temperature on the adjacent land and over the surface of the ocean. The range of temperature over the oceans between summer and winter months is very insignificant. Hence the temperature curves for the places over or near the sea are almost straight, as we can see in the case of harbours and ports.

In the heat balance or the heat budget of the ocean, atmosphere plays an important role but the effect of oceans on temperature and humidity of the atmosphere is far more significant because to warm the same volume

of air and water by 1° there is need of 3000 times of greater energy for the sea water. The release of this heat energy from the oceans into the atmosphere in the form of water vapour and its condensation in the atmosphere greatly influence atmospheric temperature conditions which control climates of the regions. The major contrast between the effects of land and water on temperature conditions and their geographical distribution may be visualised in the two types of climates of the world, viz. the continental and the maritime climates. The main factor is the nature and amount of heat radiation from the sea surface and land surface and their heat absorption rate.

The currents of the ocean modify the distribution of temperature along the coast. Sometimes they bring into an area the water that is abnormally warm and into another area the water that is abnormally cold. The influence of the currents depends upon their character and nature. For example, the climatic conditions of east coast of North America and west and north-west coasts of Europe are governed by the warm water of the Gulf Stream. The West European or the British type of climate of Europe is also partly due to the Gulf Stream.

Fig. 95 in the chapter on "Currents of Atlantic Ocean" shows the effect of the Gulf Stream on temperature distribution of the coastal areas and waters of the mid-Atlantic. The shaded area shows the regions of 4° F warmer than average temperature of sea water in those latitudes. Further, in southern hemisphere between 0° and 40° latitudes the warm water comes on the western side of the ocean along South American coast and cold water upwells along the eastern side of the ocean. This creates temperature contrast between the two coasts in same latitudes. This may well be exemplified by the east coast of South America and west coast of Africa.

Further, poleward of the latitude of 40° in both the hemispheres, the west coasts are warmer than the east coasts due to warm drifts and cold polar currents respectively. They make the temperature conditions of the coast of Norway moderate which would otherwise not have been the case in those latitudes. The examples of other currents of the Atlantic like Labrador and East Greenland current also influence the climate of the affected coastal areas. The British meteorologist C. E. P. Brooks compares the Gulf Stream with a hot tap and the Labrador and E. Greenland current with two cold taps in the Atlantic Ocean. These determine the surface temperature and weather of Europe and of Arctic region.

As a matter of fact, these ocean currents cause the redistribution of heat over thousands of miles and make up for the uneven heating of the globe. A reference to the climatological charts of the oceans will clearly demonstrate the relation between oceanic circulation and climates of the continents.

The impact of oceans on climate will be more clear when we consider the distribution of pressure and prevailing wind system over the sea surface. The pressure distribution over the surface of the sea influences the world's climatic phenomena, as the oceans have six or more permanent centres of high pressure and these high pressure areas are the birth places of circulation of winds over the earth. The prevailing winds determine the amount of rainfall and its distribution over the earth surface, i.e. the rainfall distribution over European continent is only due to the westerly winds which blow

from the Atlantic Ocean, from where they take moisture; the east and south-east coasts of U.S.A. also get the rainfall because of the winds coming from the Gulf of Mexico and from the tropical waters of the Atlantic Ocean.

Various theories have been evolved about the long period climatic cycles and the control of oceans over those cycles. Otto Pettersson puts forward his concept of long period climatic changes and relates it with the oceanic conditions. This theory of climatic variation was based on scientific, historical and literary evidences and showed that there are alternating periods of mild and severe climates which correspond to the long period cycles of the oceanic tides. According to him, the period of maximum tides and most rigorous climate occurred recently in the year 1433, whereas the time of minimum tidal phenomena took place at about 550 A. D. and will occur again about the year 2400 A.D. C.E.P. Brooks is one of those who appreciated the above concept and remarked: "It seems that there is good support for Pettersson's theory as well as for that of solar activity and that the actual variations of climate since about 3000 B.C. may have been to a large extent the result of these two agents, namely, tidal phenomena and solar activity.

Oceans and food resources. The sea as a biological environment is the source of food and other products of value to man. It is the easiest available and inexhaustible source of food supply. There is no need to cultivate land and wait for the maturity of crops as in agriculture. With the progress of human society and with the increasing population, the dependence of man on sea as source of food has been increasing constantly.

The first great centre of marine biological research was founded by the German Anton Dohrr in Naples (1872). Later on, it was followed by the formation of Marine Biological Association and the establishment of an aquarium at Plymouth in 1884. During the first quarter of the present century in the various countries of Europe, North America and Japan, efforts to develop the sea environment as a source of food have resulted into the establishment of various scientific and research bodies and institutions of oceanic research, viz., International Council for Exploration of the Sea, Copenhagen (Denmark); North American Fisheries Council; Hydrographic Biological Commission, Sweden; the Oceanographic Institute in Paris; the Monaco Oceanographic Museum; the Naples Zoological stations; the Biological Board in Canada; Scripps Institution of Oceanography; and the Woods Hole Oceanographic Institution in U.S.A. etc.

Sea water is the most appropriate environment since it contains all the chemical elements essential for plants and animals. It has a wide range of living conditions based on the amount and distribution of salinity, temperature, sunlight, pressure and constant motion. The magnitude of the sea environment may be visualised by taking into consideration its geographical aspects. The oceans, covering 71% of the earth surface with their great vertical range for marine life, form one of the three principal biocycles, namely, terrestrial, marine, and fresh water biocycles. "It is estimated (Schmidt 1937) that the marine environment actually provides about three hundred times the inhabitable space provided by the terrestrial and the fresh water biocycles together."¹

¹ Sverdrup and Others, *The Oceans*, p.274.

The relationship of marine population with the physical and chemical properties of the sea environment is very close and complicated. The various conditions of sea control the population of the water in many ways.

The first factor, the factor of light, is directly concerned with metabolism of the organisms and is a source of energy for the photosynthetic processes. These in turn influence the total wealth of the sea water and its variations according to the depth of the water body. Further, the colour of the sea animals is also due to the light factor according to the varying degrees of depth. But this light, depth and colour relationship changes according to the latitude of the locality. According to Hjort (1912), 'forms occurring at about 200 to 500 m in the higher latitudes between about 67° and 50°N will be found near 750 m at the latitude 33° N.' The investigations made by 'Michael Sars' at about 35° N, show that dark colour is due to greater depths.

The second factor responsible for the varied life of the sea is the factor of salinity determining the extent of Stenohaline animals, sensitive to small changes in salinity; and Euryhalines, having a great degree of tolerance to the change in salinity.

The third factor of temperature influences the biological phenomena of the sea. The sea temperature has the range from 3° C to 42° C. This determines the various animal and faunal zones. Further, the temperature also decides the size of the animals: cold water animals grow to a larger size than do similar animals in warm water.

Further, the oceanic movement in the form of currents causes many variations which are important in the marine life. The more important aspect of sea movement is the moderating effect of currents over the living conditions of marine organism. "The character of the fauna and flora is thus governed by the nature of the currents—namely their origin, direction of flow, magnitude, coldness or warmth, degree of salinity or density, and their character as regards other attributes such as relative richness in nutrients." Further, the importance of currents lies in the dispersal of marine life and examples are enough to prove the trans-oceanic transportation of organisms.

Fish form a rich source of food and nutrition to man. Fishing has long been the economic activity of variable importance in all the latitudes. It is regarded as the oldest occupation of man and now all the great maritime nations have well developed fishing industry.

Fisheries have played a part in the destiny of nations. The rise and downfall of nations have been the result of the prosperity and decay of the industries connected with fisheries. The Hanseatic League from the small beginnings of the herring fisheries in Scania rose to a power of great magnitude. The rise of the sea power of the Dutch in 17th century came as the result of development of fisheries in the North Sea. The Tudors in England feared a loss of sea power with the decline of the fisheries. The progress of fisheries also resulted into the development of mercantile marines and the royal navy.

The location and extent of commercial fisheries in comparison to the great extent of oceans is very restricted but the fish as an inexhaustible

source has the incredible capacity for multiplying. The wanton exploitation and dwindling local supplies affected the commercial fishing in some areas.

The world's important fisheries are of three general types: (a) Inshore, (b) Pelagic, and (c) Demersal. The general distribution depends upon the spawning habits of the fish and the presence of food. Because of certain advantages the world's greatest fishing centres are found over the continental shelves of the shallow waters of the (i) north-western Europe, (ii) north-eastern North America, (iii) north-western North America, and (iv) north-eastern Asia.

Japan has the largest fishing industry amounting to 4.0 million metric tons as compared to 2.5 million metric tons of U.S.S.R., 2.4 million metric tons of U.S.A., 1.3 million metric tons of Norway, and 1 million metric tons of U. K. The value of the catch of the fisheries of the world is smaller in comparison to the returns from many other economic activities of man on the land, the average annual total of about \$ 700,000,000 being less than that of a single important crop such as corn or cotton or it is less than the total value of eggs and poultry sold in U.S.A.

The temperate zone fisheries have the largest amount of commerce and trade. Here are the world's largest fisheries in the shallow waters of the North Atlantic and the North Pacific oceans. The north-west European area or the North Sea with its Dogger Bank comprise the greatest fishing region in the world. The important fish are cod, herring, and haddock. The fishermen include the Scandinavian, the British, the French, the German, the Dutch and the Iclander, approximately numbering 200,000 and their annual catch is about 4,000,000,000 pounds. It is the leading area for the export of fish in the world.

The North Atlantic fisheries of the U.S.A. and Canada have been of great importance for several hundred years. The fishing banks extend along the coasts of New England and eastern Canada from Nantucket Island to Newfoundland and into the Gulf of St. Lawrence. The cod, haddock, herring and other species rank high in tonnage. These fishing grounds owe their importance to a combination of favourable conditions due to the waters of cold Labrador meeting the warm waters of the Gulf Stream over the extensive shallow continental shelf. Here the largest and the most important area is the Grand Bank, south-east of Newfoundland, where 37,000 sq. miles of the ocean bottom which is less than 360 feet in depth is most suited.

On the other hand, the fisheries of the Pacific coast, that is, of north north-western America between the northern California and the Bering Sea, now ranks among the world's greatest fisheries. The important catch consists of salmon, halibut and herring. It has been an important industry on the Pacific coast for nearly 100 years where the salmon industry is the most important one.

The fisheries of Asiatic land is formed by the Japanese waters. The Japanese people catch and eat more fish than any other people in the world. As a result of the world war, the industry declined considerably in recent years. The meeting of the two ocean currents, the Kuroshio and the Kurile, and the long indented coastal line make these waters important.

The importance of fisheries is enhanced further in Japan due to large population concentration and very limited agricultural area.

Further, in comparison with the temperate fishing grounds, the tropical waters are poor and commercially unimportant. Fishing in these waters is important as the source of food and not of trade and commerce. The important areas are the south-east Asian waters and the Gulf of Mexico etc.

Ocean and politics. The ocean plays a major role in the geo-political set up of the world. Its universal and overwhelming influence upon man matters significantly in world politics. The oceans as an economic asset, due to their rich faunal wealth and due to being the easiest link of communication between the various regions of the world, form the nucleus of conflict between the world powers.

Since ancient times, the sea has been a centre of great activities and of political interest. In the classical period when the world was limited to the extent of the Mediterranean and the neighbouring land mass, the Mediterranean Sea was the pivot of power politics for the Greeks, the Romans and the others. Gradually with the progress in discoveries and explorations, the extent of the sea and the world became more wide. In and after the Great Age of explorations in the 14th and 15th centuries, the conflict over the sea shifted to other regions. Later on, with the development of trade and commerce and with the establishment of empires in south-east Asia, Africa and the Americas, the sea and oceanic routes became more important strategically and became the lines of greatest tension in the world politics. Hence the role of sea in the world political set up assumed great magnitude.

In the first half of the present century, three sets of geographical conditions affecting the use of the seas have emerged, viz. increase in sea borne trade, quest and search for markets and sources of raw materials, and growth of the new navigational aids etc. These resulted into an unprecedented growth of maritime traffic and close international relationships. F. Osborne rightly remarks : "The ocean was one ocean all the time, but the practical meaning of that great reality was not wholly understood until a few years ago; perhaps it is only now being grasped in its entirety."

The major role of oceans in world politics may be visualised by considering the major aspects of sea and its relationship with the neighbouring areas.

Sea and maritime boundaries. The growth of a number of independent states in the world after the last two world wars resulted into the need of having well defined boundaries, land as well as sea. The great increase in world population with a lower rate of increase in the production of food further enhanced the need of such boundaries.

The extent of the continental shelf and the decision of the various conferences and resolutions on the part of various countries and organisations evolved a *continental shelf theory* to delimit the boundaries. Hence International Law Commission suggested 200 m isobath line as the suitable line of demarcation of boundaries. It has been seen that this involved difficulties as in the case of the West European shelf due to the existence of so many states.

The extent of the territorial sea is a matter of great conflict and assumed a vital role in world politics. The limit of it has been generally accepted to the extent of three miles off the coast, but at present there is no unanimous agreement on this limit. Most of the states claim the three miles limit, whereas four states claim a four miles limit, one state (Honduras) claims a five miles limit, Mexico claims a nine miles limit, the U.S.S.R. stands alone in its claim to a twelve miles limit, and Chile and Peru stand for 200 miles limit. But in these days of navigation and sea-borne trade, the freedom of the high seas for various purposes is very necessary and so these maritime limits often become the source of conflict between different nations.

This geopolitical tension is further intensified when the sea is taken as the ready and most inexhaustible source of food for the growing number of the world's population. Riesenfeld remarks: "The fishery question has been the focal point of the whole problem of territorial waters from its very beginning." The multilateral convention relating to fisheries in certain waters, such as the North Sea convention (1882) and the Baltic Sea agreement has been taken as measures for an intelligent solution of the most perplexing problem of both coastal and high sea fisheries.

The occupation of mining also created complications in the national claims in adjacent seas. The lateral shaft mining up to the extent of 3 miles have been sanctioned but beyond this many frictions may arise. Recently the continental shelf as the source of petroleum has been the cause of further disturbances. According to Wallace E. Pratt, "The peripheries of the continents constitute a fundamentally superior environment for the generation and accumulation of petroleum." This characteristic will lead to more political conflicts and the question of national claims in the adjacent seas will assume greater importance.

Maritime empires and their life lines. The Great Age of discoveries and explorations and consequent establishment of empires and their expansion in the tropics resulted into the need of trans-oceanic lines of communication and transportation. The British Empire was built up along the seaways of the world. The other great empires were built only by the maritime powers like the Dutch, the Portuguese and the French. For the security and peaceful administration of these empires the seaways, with the growth of various navigational techniques, became the blood lines.

The British Empire maintained itself for a very long time on the various lines of navigation through the North Atlantic and the Indian Oceans, and on the small islands which offered ports of call at convenient intervals along a route. These lines acting as 'Jugular Veins' and islands as beads of the chain, during the time of tension, have been the source of world tension and power politics from time to time. During the times of world tension, these traffic lines magnify the importance of the sea which ultimately has been the theatre for world politics and power conflicts. At this time the justification for the huge establishment of Navy and maintenance of these life lines is seen.

Oceanic routes and international canals. The growth of world trade (export and import) and commerce enhanced the significance of sea routes and canals connecting the various seas. The role of International canals, i.e. Suez, Panama and Kiel, has been of great political significance as every

big power wanted to have a control over them. The British, the French and the Dutch attached great importance for the growth of trade and commerce and for the maintenance of their empire and so they attached equal importance to these canals. The crisis threatening world peace often came on the horizon because of these canals, e.g. the role of Suez in the recent Middle East tension cannot be obliterated.

These oceanic traffic lines have given strategic importance to various straits and narrow joining seas. The role of the strait of Gibraltar, the strait of Bosphorus, the strait of Babel Mandeb and the strait of Singapore remained of great importance and their importance fluctuated according to the world politics, as they have always been the weak points for world peace.

In fact world politics and oceans are intimately associated with each other. More than land, ocean has been a source of world tension and power conflict. During the classical and up to the middle century the role of the Mediterranean was very great. After a period of insignificance, the construction of the Suez canal again brought back its importance. Time and power politics change the role of various other water bodies. The Arctic Ocean, once a useless waste, is becoming the theatre of world politics due to great advances made by U.S.S.R., U.S.A. and Canada.

Ocean transportation and trade. The ocean as a highway has been the initial means of opening up of new regions for settlement and economic colonisation. It is the most important means of transport which nature has provided. As oceanic environment is forming 71% of the extent of the earth surface, the sea water forms the easiest means of transport for the nations of the world. The nation without sea frontage is said to be just like a house that is not upon a street.

History tells us the importance of sea frontage in the life of a nation. The political strifes and struggles arose on the question of sea front. "This is because the oceans form a world highway that belongs exclusively to no one, reaches everywhere and can be used by each and all that possesses a bit of its shore."

Previously there was a time when oceans were looked upon as barriers separating continents. Now the relative cheapness of ocean transportation is the main cause of importance of oceanic trade in the world. The cheapness is due to the fact that nature provides free highway, the water is buoyant, needing less motive power.

The nature of the ocean routes and their determination is the result of various factors : the facilities for coaling at intermediate stations, the great circle routes, the presence of ice, the prevailing winds, fogs and the ocean currents, and cargo possibilities, etc. So the ocean route is an avenue along which, because of one or more of the above factors, the tracks of numerous ships converge or coincide.

The North Atlantic Route, connecting eastern North America and Western Europe, is the busiest ocean trade route and it employs one-fourth of the world's merchant vessel tonnage. No other route equals it

in the value, volume of the freight traffic and the total number of passengers. This top rank as assigned to this route is due to the characteristic richness of two areas connected with this route. They are most populous and highly developed regions of the world, surpassing all other in manufacturing, transportation, finance and trade. So between the regions of West Europe and North America, many hundreds of vessels traverse the North Atlantic Ocean. Further, an unusually high proportion of the world's great ports serve the route as terminals.

Besides this route in the Atlantic, the other important routes are the routes of the Caribbean America connecting the west coast of Europe with the West Indies and west coast of South America; the South American route between the Plate valley and western Europe; and the route connecting the west coast of Europe and west coast of South Africa better known as South African Route. The characteristics of these above routes are the transport of raw materials, food stuff, etc. from South America and West Indies to West Europe and the transport of finished and manufactured goods from Europe to these countries of South America and Central America.

Further, at Panama Canal the routes are focussed mainly from three sides : (a) between the east and west coasts of U.S.A., (b) between either side of the North Atlantic and the west coast of South America, (c) between eastern U.S.A. and eastern Asia and Australia. The importance of the canal is because of the fact that it has reduced the total length of the various routes between the west coast of South America and west coast of Europe and between the east and west coast of U.S.A. It has given the greatest benefit to the inter-coastal trade.

The Mediterranean Asiatic route or the Suez route connects the whole of the North Atlantic region with the south-eastern Asia and Australia. The important date for this route is 1869 when Suez Canal connected the Red Sea and the Mediterranean Sea. This route pierces the heart of the world, for it serves most of the land area and most of the world's population and circumnavigates the vast, irregular continents of Eurasia. It has been of great importance to the colonising countries of Europe, i.e. Great Britain, Holland, France, Denmark, Portugal and Spain. To Great Britain it has been the 'Jugular Vein' of the Empire.

On the population basis it serves three-fourth population of the world, that is 21,00 million population of the continents of Africa, Europe and Asia and connects two type of culture and civilizations of the world. Of all the world's ocean routes, it is the trunk line par excellence. The Mediterranean route forms the most strategically important area of the world because of the petroleum resources of the Middle East countries. In times of war, it became the main centre of politics because it served the major portion of world where several types of social and economic orders prevail. It is served both by raw materials and manufactured goods from south-east Asian and European countries respectively.

Other routes are the South African route, which is an alternative to the Mediterranean Asiatic route. It connects the southern part of Australia and Europe via west coast of Africa. Further, among the trans-

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Pacific oceanic routes, the New Zealand Cape Horn route, the west coast of North America and East Coast of China-Japan route are very important.

The above survey of the oceanic routes of world clearly brings out the fact that oceans are the most vital factor of communication on the global basis. The world's economic prosperity, trade, and population concentration are to a greater extent influenced by the oceanic environment.

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